S100 24 and 25

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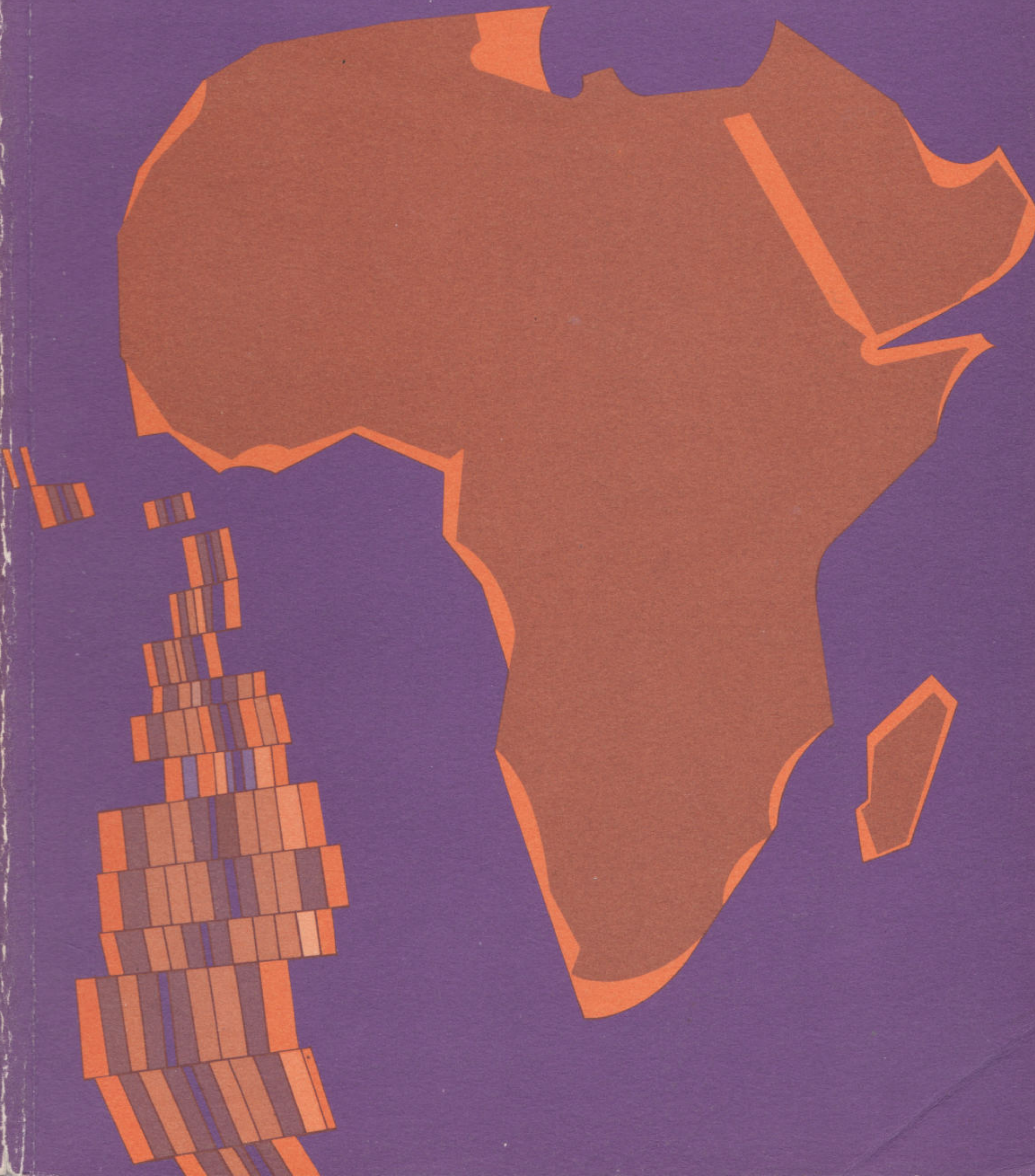
Science Foundation Course Units 24 and 25

Major features of the Earth's surface
Continental movement, sea-floor spreading and plate tectonics



The Open University

Science Foundation Course Unit 25

CONTINENTAL MOVEMENT, SEA-FLOOR SPREADING AND PLATE TECTONICS

Prepared by the Science Foundation Course Team

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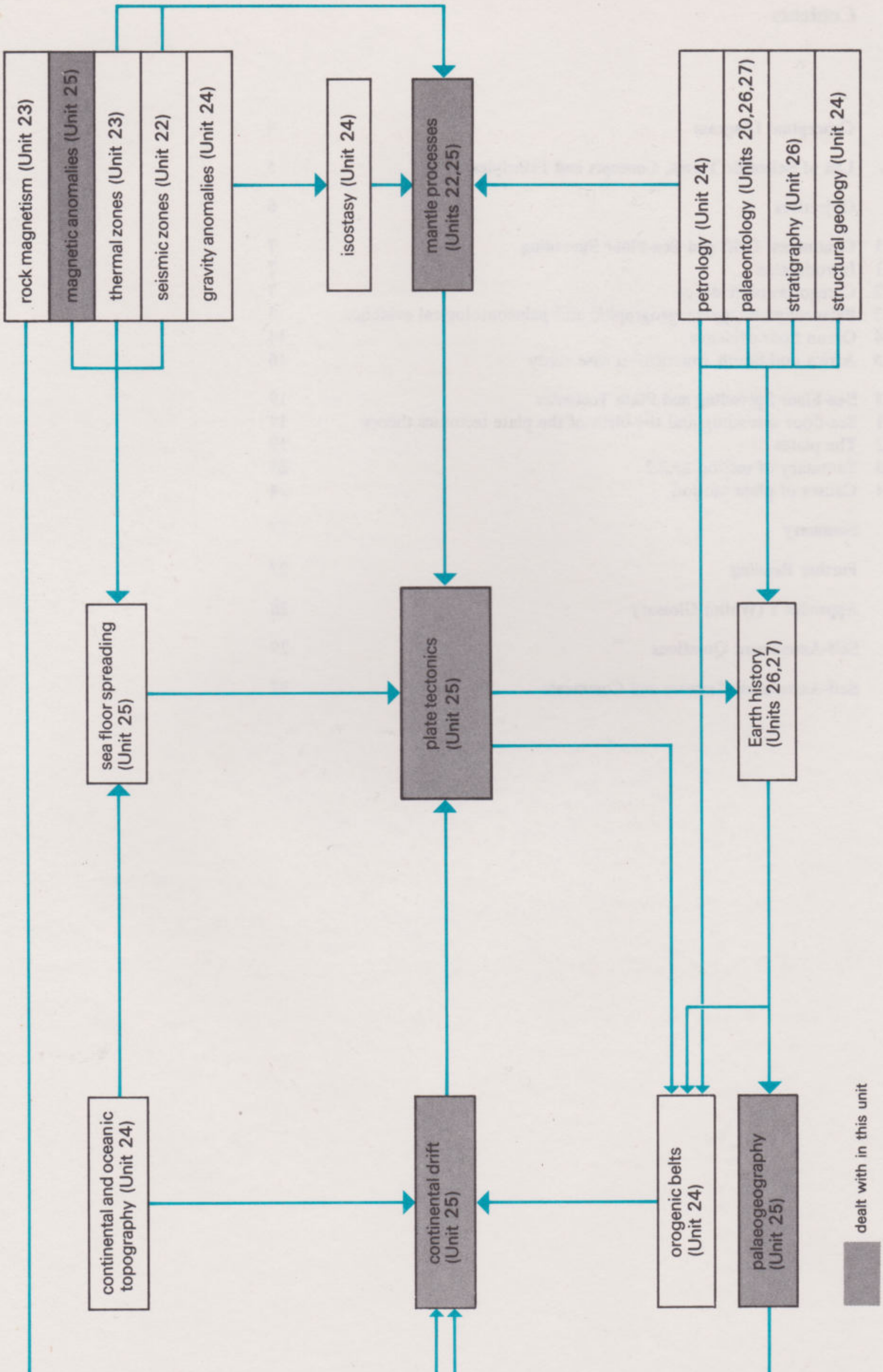

rock magnetism (Unit 23)
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seismic zones (Unit 22)
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continental drift (Unit 25)
orogenic belts (Unit 24)
palaeogeography (Unit 25)
dealt with in this unit

Table A

List of Scientific Terms, Concepts and Principles used in Unit 25

Taken as pre-requisites			Introduced in this Unit			
1	2		3		4	
Assumed from general knowledge	**Introduced in a previous Unit**	**Unit No.**	**Developed in this Unit or in its set book(s)**	**Page No.**	**Developed in a later Unit**	**Unit No.**
continental	basaltic ocean		*In Unit*		stratigraphy	26
movement	floor	22	continental drift	7	palaeontology	26
oceanography	Earth's rotational		fit between continental margins	7		
latitude	axis	22	climatic zones	8		
longitude	Chandler wobble	22	Earth's radiation balance	8		
convection	Coriolis force	22	palaeoclimates	8		
fossil	magnetic reversal	23	polar wandering curve	8		
	magnetic chronology	23	circulatory cells	11		
	seismic refraction		isobars	11		
	techniques	22	spreading rate	16		
	ocean ridges	24	plate tectonics	19		
	oceanic trenches	24	sea-floor spreading	19		
	magnetometer	23	aseismic zones	20		
	earthquake focus	22	types of plate margin:			
	epicentre	22	constructive	20		
	lithosphere	22	destructive	20		
	seismic zones	22	conservative	22		
	Moho	22	convection currents	25		
	mantle	22				
	asthenosphere	22	*In Understanding the Earth*			
	low-velocity layer	22	tillites	31		
	Benioff zone	22	evaporites	32		
	gravity anomaly	24	Gondwanaland	212		
	island arc	24	Permo-Carboniferous glaciation	218		
	orogenic belt	24				
	continental belt	24				
	continental slope	24				

Any scientific terms used in this Unit but not listed above are marked thus † and defined in the glossary (p. 28).

Objectives

When you have completed this Unit, you should be able to:

1 Define correctly in your own words, or recognize the best definitions of, or distinguish between true or false statements concerning each of, the terms, concepts and principles listed in columns 2 and 3 of Table A.

2 Correctly list, or recognize from given examples, the five major lines of evidence favouring the theory of continental drift.

3 Correctly recognize the roles played by atmospheric radiation balance and the Coriolis force in determining the positions of climatic belts.

4 From given data, distinguish similarities between the palaeoclimates of continents caused either by similar latitudinal positions or by the former juxtaposition of the continents concerned.

5 Recognize, or correctly identify, evidence favouring sea-floor spreading.

6 Given palaeomagnetic data, calculate rates of sea-floor spreading, and suggest dates at which continents began to drift apart.

7 Distinguish between observational results and hypotheses concerning sea-floor spreading, and spreading rates.

8 Indicate how seismology has contributed new data leading to the formulation of new ideas concerning the structure and behaviour of the outer part of the Earth's crust.

9 Correctly identify, from given data, constructive and destructive plate margins.

10 Recognize the geophysical evidence which favours convection theories for crustal movement.

COURSE OBJECTIVE

THE CONCEPT OF CONTINENTAL DRIFT, BASED UPON 'LAND-BOUND' DATA, AND

THE CONCEPT OF SEA-FLOOR SPREADING BASED UPON STUDIES OF THE OCEAN FLOOR

Section 1

25.1 Continental Drift and Sea-Floor Spreading

25.1.1 Introduction

In the last Unit we suggested that relative lateral movements of the continents have occurred. You probably assumed that such evidence comes mainly from a study of the oceans—especially from the oceanic ridges, which appear to be formed by the continuous intrusion or 'upwelling' of new basaltic ocean-floor material. Such oceanographic evidence has proved to be crucial to demonstrating that lateral continental movement (i.e. continental drift) has occurred. Yet the first suggestions that such movement had occurred were made on land-based evidence. Therefore, this Unit commences with a discussion of such evidence, which includes results collected by stratigraphers (geologists who unravel Earth history from rock successions), palaeontologists (geologists who study fossil remains), structural geologists and geophysicists. When you have read about this evidence, you may feel it to be pretty conclusive, but twenty or thirty years ago it did not seem so to many geologists. However, once evidence became available from the oceans, few sceptics remained. The second part of this Unit is concerned with evidence, derived from study of ocean floor, of continental movement.

Finally, possible mechanisms to explain lateral crustal movements will be discussed. As you will see, this field of study has yielded an apparently simple theory which unifies many disciplines and explains in a coherent way the Earth's surface and crustal features which have been described in earlier Units.

YOU SHOULD NOW READ THE TV BROADCAST NOTES FOR THIS UNIT BEFORE CONTINUING WITH THE TEXT

25.1.2 Categories of evidence

The five main lines of evidence which support the theories of continental drift and sea-floor spreading are presented below. You have briefly met some of them in previous Units, and others will be explained here. You will be assessing some of the evidence for yourself by completing the exercise in section 25.1.5.

1 Topographic fit between the continents

If you look at any atlas map, you will see that the coastlines on either side of the Atlantic have roughly similar shapes. But remember that the coastlines are not the real continental margins (see Unit 24), which lie somewhere on the continental slopes. It has been found that there is an extremely good topographic fit between the margins of the 'geophysical' continents. Having estimated the best topographic fit, we then have to compare the geology across the join, such as rock successions, the fossil fauna and flora they contain, and orogenic belts.

2 Fit of orogenic belts between the continents

We saw in Unit 24 how around the Pacific Ocean the most recent orogenic belts are parallel to the continental margins (see Fig. 9, Unit 24). Around the Atlantic, however, there are orogenic belts which are truncated at the continental boundaries. Oceanographic evidence shows that these linear belts do not continue across the ocean floors, as one might expect. However, when making topographical fits of the continents, it is often found that orogenic belts of the same age are aligned across the join, presenting persuasive evidence for the validity of the join.

3 Palaeoclimatic, palaeogeographic and palaeontological evidence

This is explained at length in section 25.1.3 below.

4 Palaeomagnetic evidence

This is based on palaeomagnetic observations described in Unit 23. The data is plotted as polar wandering curves† (see post-broadcast notes for TV Unit 24), which show that the continents must have drifted apart at certain times.

5 Ocean floor evidence

This is described in section 25.1.4 below.

25.1.3 Palaeoclimatic, palaeogeographic and palaeontological evidence

Consideration of the palaeoclimatic and palaeogeographic evidence for continental drift boils down to working out what the environment was like, say 200 Ma ago, for any two continents that are thought to have drifted apart. If the ancient surface environments were vastly different (one covered in ice, the other in equatorial forests) it is unlikely that the two continents were together at the time in question. But if they experienced similar climates, the possibility of drift having occurred is much more likely but far from proved, as even today widely separated continents experience similar climates (e.g. equatorial Africa and equatorial America). So, having shown that two continents had similar climates in the past, the next step is to try and match details of their ancient geographies, such as shorelines, river patterns, freshwater areas and so on. If these match up well, the possibility that the two continents have been together in the past is obviously enhanced.

Just as the remanent magnetism of rocks can indicate the latitudinal positions of continents for past epochs, so can the distribution of ancient climatic belts, as deduced from the composition, structure and fossil content of sedimentary rocks. But if we are to arrive at meaningful conclusions about the distribution of ancient climates, we should first examine the assumption that climatic belts have born a fairly constant relationship to latitude throughout geological time.

Climatic belts. This assumption is based on a theoretical model for atmospheric circulation, which is governed by the Earth's radiation balance. On geophysical grounds we believe that the Earth's rotational axis has kept a constant angle to the plane of the Earth's orbit around the Sun (the ecliptic) through geological time. Apart from the relatively minor Chandler Wobble (Unit 22 and Chapter 6 of the *Understanding the Earth*), any departure from this position would have had catastrophic effects. Therefore, the radiation balance of energy entering and leaving the atmosphere must have remained relatively constant over the last 1 000 Ma, although before that it might have been changed by a markedly different atmospheric composition as we shall see in Unit 27.

Figure 1 shows that radiant energy from the Sun provides the energy to drive the atmospheric circulatory system. You can see from this figure that radiant energy is absorbed and re-radiated by both the atmosphere and the Earth's surface. The overall radiation balance varies according to latitude (Fig. 2) with incoming radiation exceeding outgoing radiation only at latitudes lower than 35°. This is largely due to the angle at which the Sun's rays strike the Earth's surface (Fig. 3). This means that equatorial regions of the Earth are heated, whereas polar regions are constantly cooled by radiation outward into space from the Earth.

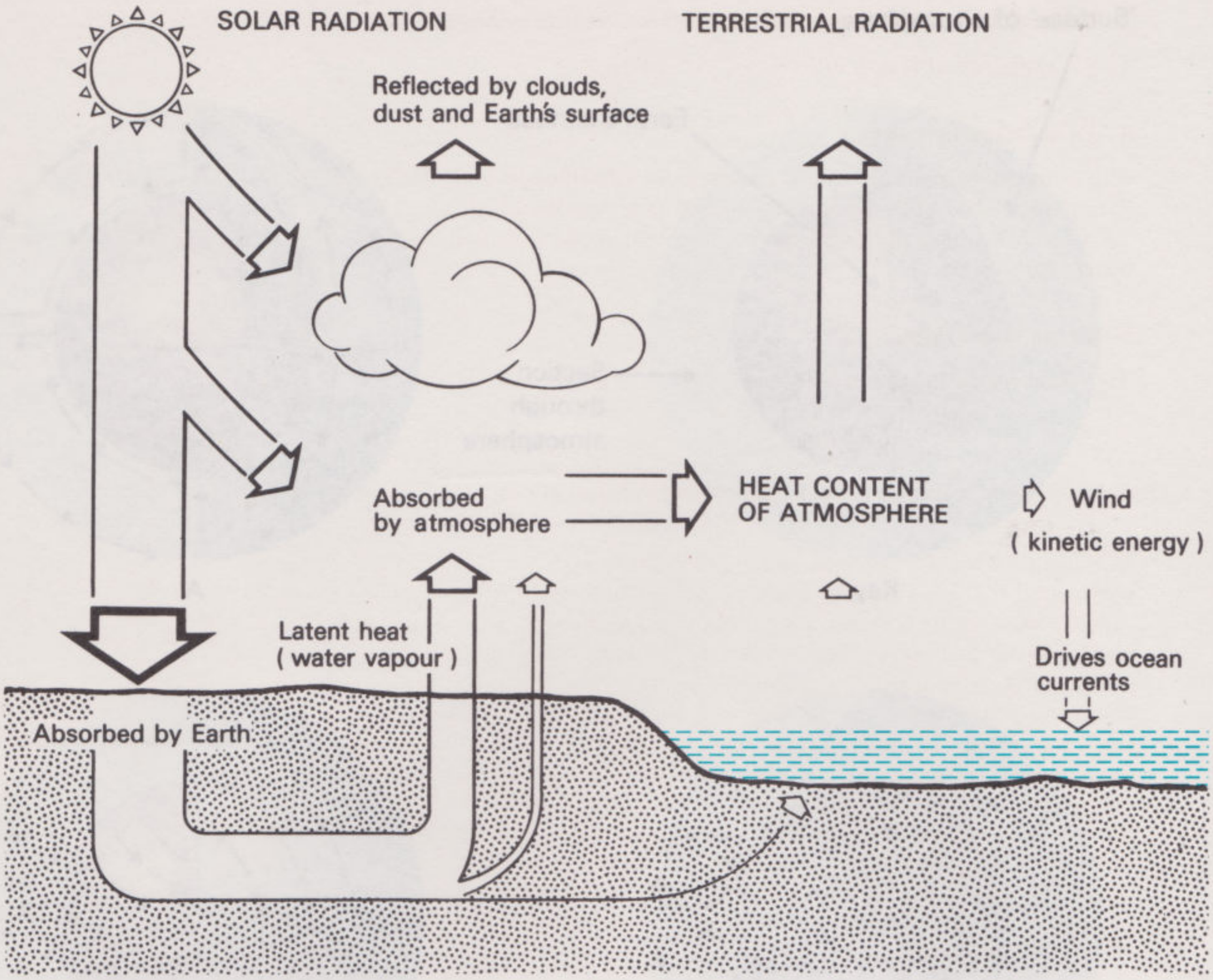


Figure 1 *Energy flow of the atmosphere.*

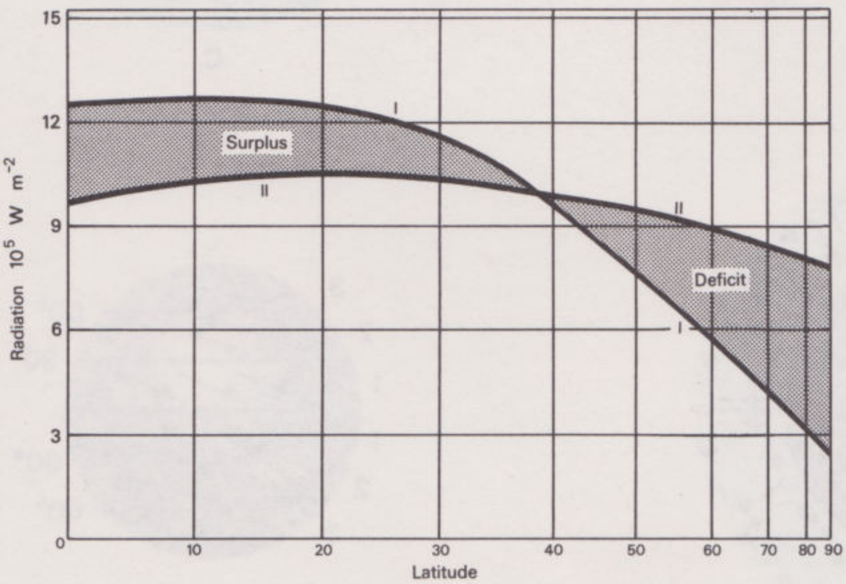


Figure 3 2 *The Earth's heat budget: curve I shows input of thermal energy from sun; curve II shows loss by re-radiation from the Earth.*

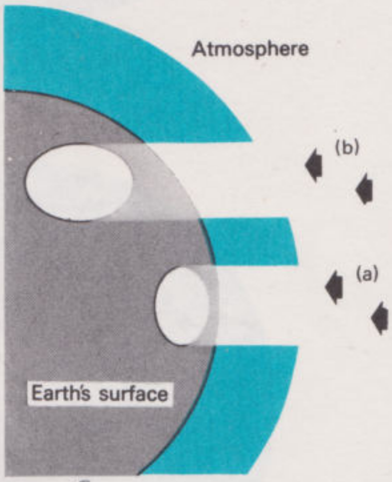


Figure 2 3 *Diagram to show that amount of solar radiation reaching the Earth's surface decreases toward the pole.*

(*a*) *Shows that rays pass through less thickness of atmosphere near the equator than they do at the poles.*

(*b*) *At higher latitudes, ray 'pockets' of same diameter are spread over greater areas.*

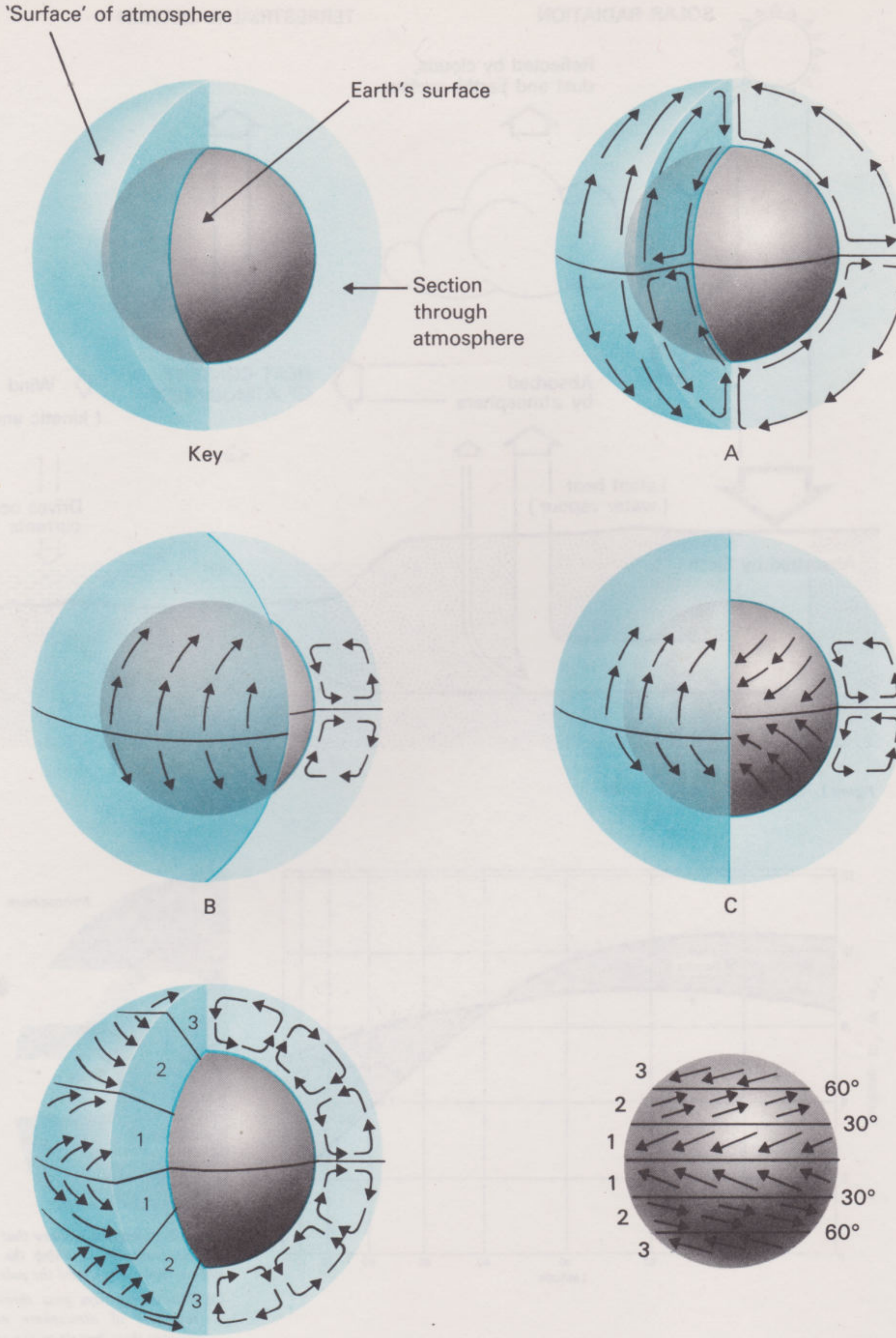


Figure 4 Idealized model of Earth's atmospheric circulation. (*For detailed explanation, see text.*)

If the Earth was not rotating, a very simple circulatory pattern would be produced as shown in Figure 4 A. Hot air rises at the equator, and then moves northward and southward to each pole, where, because it has cooled, it descends and flows back towards the equator to complete one circulation cycle. In this simple model for a non-rotating Earth, there are two circulatory cells which produce a belt of low pressure on the Earth's surface at the equator, and regions of higher pressure at each pole. In the upper atmosphere, pressure is high at the equator and low at the poles. The next stage in developing a model of the Earth's circulatory system is to consider the effect of the Earth's rotation on this simple pattern. This effect has already been discussed in Unit 22.

Can you remember its name?

Remember that the Coriolis effect (force) causes any particle moving across the Earth's surface to be deflected towards the right in the northern hemisphere, and to the left in the southern hemisphere. Winds are of course affected by the Coriolis force. Without it winds would blow from high pressure to low pressure regions at *right angles* to the isobars†. But from weather maps, such as those in newspapers or on TV, you must be aware that this does not happen. The wind direction, being deflected by the Coriolis force, is almost parallel to the isobars. The overall effect is that the wind pattern 'spirals in' towards low-pressure areas; in fact in the northern hemisphere, if you place your back to the wind, the low-pressure area will be to your left. In other words, in the northern hemisphere, wind blows around a depression in an *anti-clockwise* direction. In the southern hemisphere, of course, the opposite is true.

Figures 4 B and C show how the original double-cell model is modified by the Coriolis effect into a number of subsidiary cells. Figure 4 B shows the effect of the Coriolis force on the warm air rising at the equator—it is deflected eastwards as it moves north or south. As the air moves away from the equator, the Coriolis effect increases and exceeds the 'convective force', so that air begins to return to the equator. It is prevented from doing this in the upper atmosphere by other 'parcels' of air taking similar paths. However, as the air moves from the equator it cools, becomes denser, and so sinks back into lower levels of the atmosphere, as shown on the right-hand side of Figure 4 B. The air then returns to the equator near to the Earth's surface, *where its motion is again subject to the Coriolis effect*; this is shown in Figure 4 C. Thus the air circulates not in a simple two-dimensional cell (as viewed in a section perpendicular to the Earth's surface), but in a three-dimensional one. Now Figures 4 B and C do not show atmospheric circulation beyond this tropical cell. However, the air on the poleward sides of these tropical cells is warmer than that actually at the poles, so convection will continue towards the poles. The circulation is completed by two further cells, shown as 2 and 3, in Figure 4 D. The surface winds produced by these cells are shown in Figure 4 E. Here, cell pair 1 (in northern and southern hemispheres) produces the NE and SE trade winds, and so these are termed the trade wind cells.

At the junctions between each cell occur the doldrums, where wind speeds are generally very low. Cell 2 produces the westerly winds of both hemispheres, and cell 3 the easterlies of polar regions.

The energy balance of the Earth's atmosphere is therefore maintained by a more circuitous route than that which would occur on a non-rotating Earth. The main region of mixing of cold polar air and warm tropical air takes place between cells 2 and 3; in fact pockets of warmer air migrate northwards into the colder polar air. These pockets are the familiar 'lows' (low-pressure areas) of weather maps. As the British Isles are situated in this zone of mixing, such 'pockets' traverse the country regularly, accounting for our variable climate.

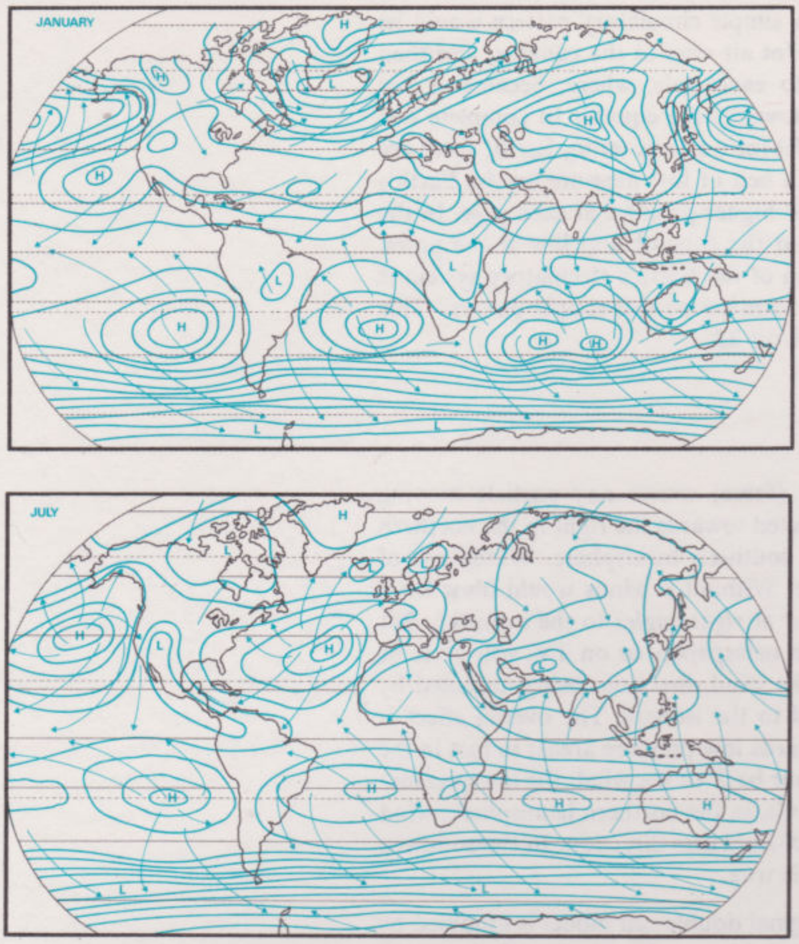


Figure 5 Seasonal changes in wind patterns over the Earth's surface (indicated by arrows) and average barometric pressures (plotted as isobars) compared with idealized model of circulatory system.

On a non-rotating Earth, winds will flow out radially from the centre of a high pressure area, and inwards towards a low pressure area. However, as you can see from the maps a simple radial pattern does not occur, but the winds are deflected. If you look at the July map, anticyclones in the Atlantic show this very well, in the northern hemisphere the winds are deflected to the right (facing their direction of movement) and to the left in the southern hemisphere.

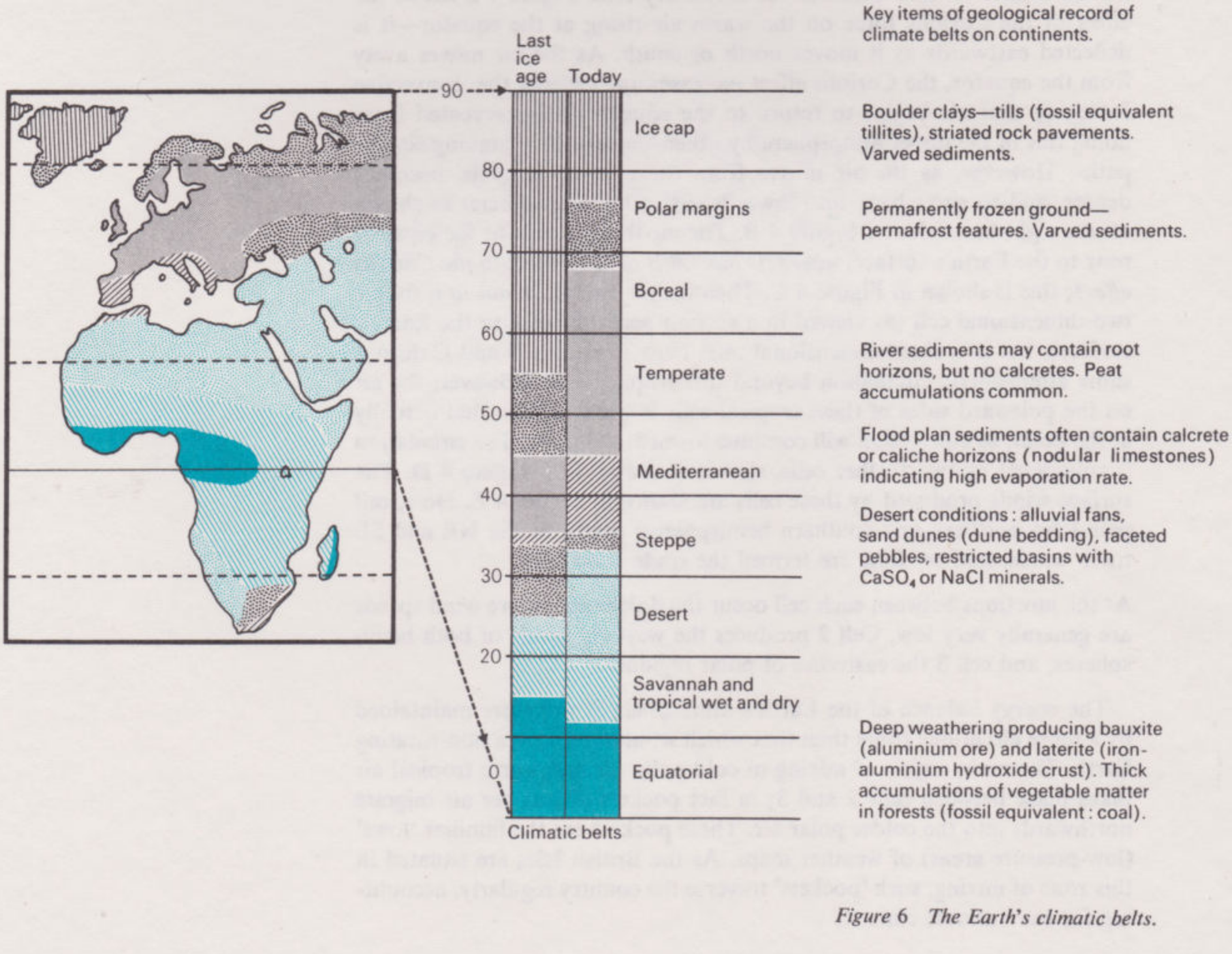
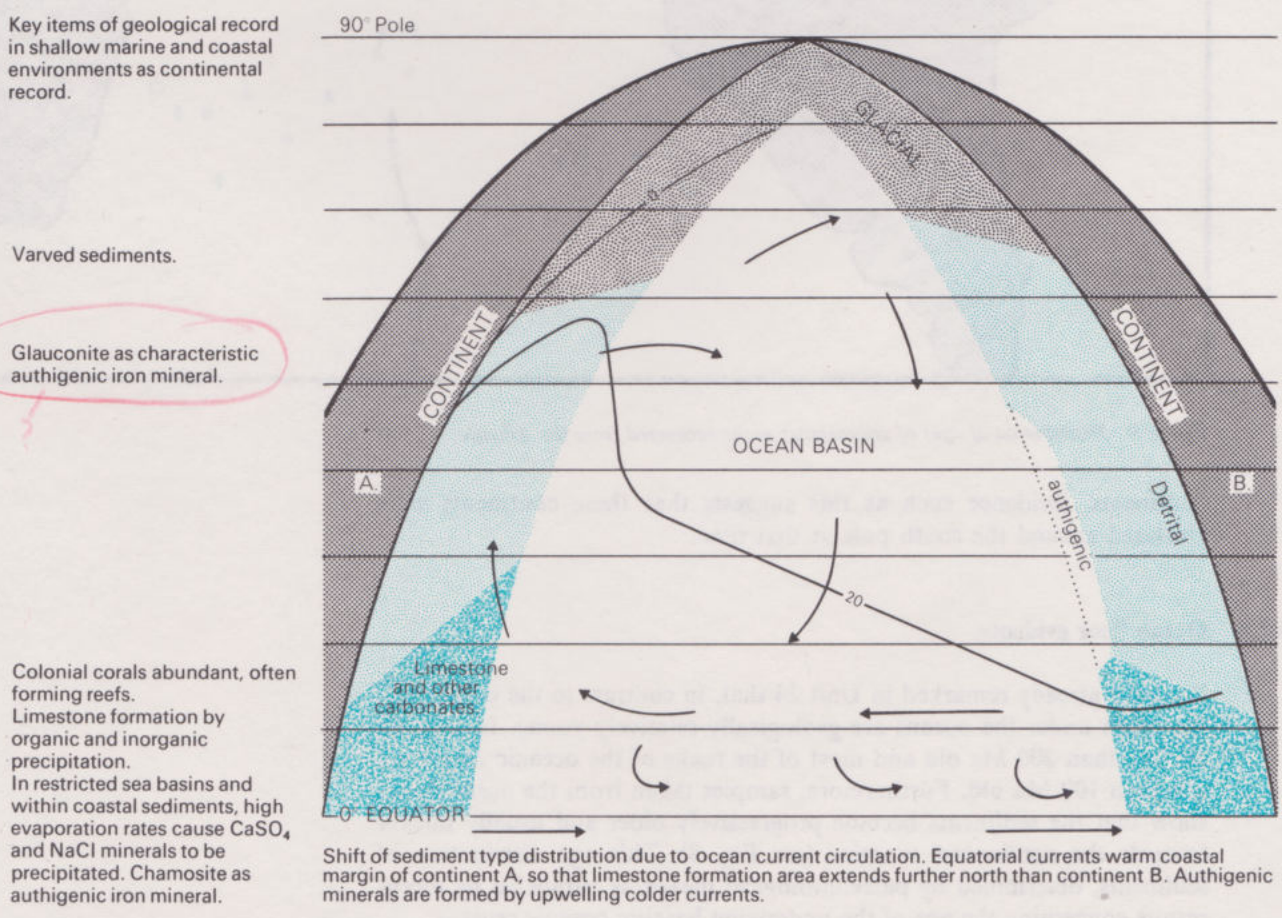


Figure 6 The Earth's climatic belts.

Even this simple three-cell (six for both hemispheres) model is an over-simplification of the real situation, in which atmospheric circulation is influenced by other factors, such as the distribution of land and sea as can be seen on Figure 5. In the southern hemisphere, the junction of cells 1 and 2 is clearly marked by a line of high-pressure cells, but in the northern hemisphere this is less clear, due to the much greater influence of continental areas. However, the overall cell pattern already described can still be discerned.

It is reasonable to assume that this cell pattern has dominated the location of climatic belts in the geological past, subject to modifications caused by the distribution of the continents. Therefore it is also probable that the distribution of the Earth's climatic belts has been much the same in the past as it is today. Even in periods of extreme climatic conditions, such as the last ice age, the ordering of climate types, from the poles to the equator, stayed the same (see Fig. 6). Figure 7 shows the kind of sediments formed at different latitudes on the Earth's surface. As climate controls the different types of sediments deposited, rock equivalents of these sediments will give a guide to the latitude at which they formed. Climate controls not only sedimentary types, but also vegetation patterns and faunal distributions. As a modern example, we can cite the restriction of polar bears to Arctic regions and of penguins to the Antarctic. The warmer intermediate and equatorial latitudes have prevented migration between the two polar regions, so that the fauna in each region has evolved independently. Palaeontological studies of fossil fauna and flora in sediments can, therefore, also help us to determine the latitude at which they formed. For example, sediments of glacial origin (similar to deposits in Britain laid down by Pleistocene ice sheets), containing arctic-type flora and fauna of Permian and Carboniferous age, have been found on all the southern



Shift of sediment type distribution due to ocean current circulation. Equatorial currents warm coastal margin of continent A, so that limestone formation area extends further north than continent B. Authigenic minerals are formed by upwelling colder currents.

Figure 7 Palaeoclimatic indicators.

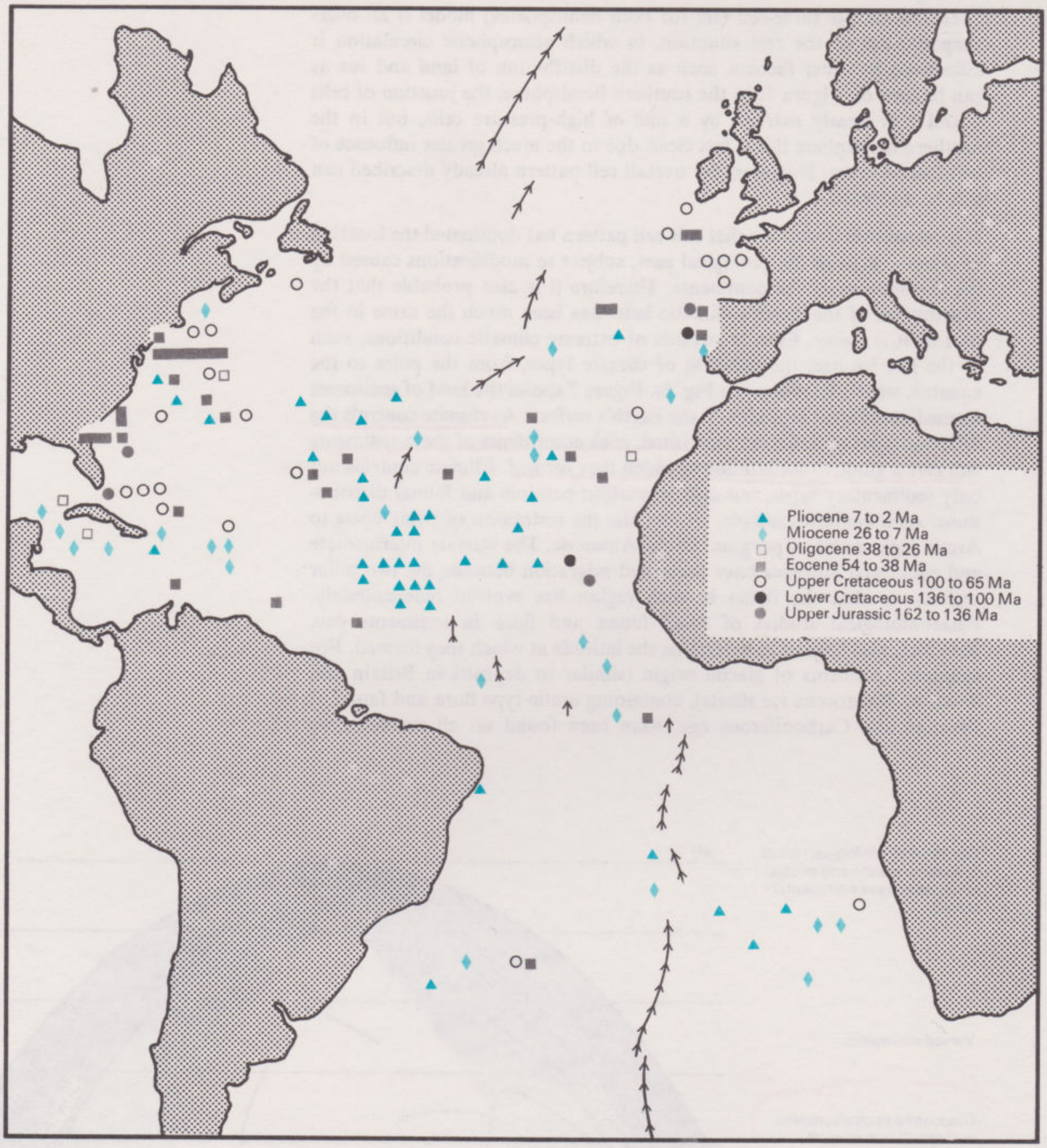


Figure 8 Distribution of ages of sedimentary rocks recovered from the Atlantic.

continents. Evidence such as this suggests that these continents were clustered around the south pole at that time.

25.1.4 Ocean floor evidence

We have already remarked in Unit 24 that, in contrast to the continents, the rocks under the oceans are geologically relatively young. In fact, all are less than 200 Ma old and most of the rocks of the oceanic ridges are less than 100 Ma old. Furthermore, samples taken from the ocean floors show that the sediments become progressively older and usually thicker towards the continental margins (see Fig. 8). This age distribution of sediments, determined by palaeontological means, is paralleled by recent results concerning the age of the underlying basaltic oceanic crust.

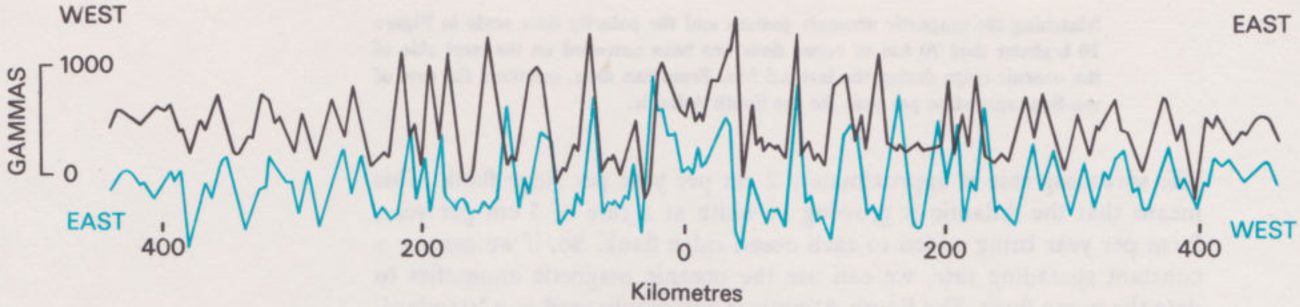


Figure 9 Magnetic anomaly profile across an oceanic ridge. Blue profile is superimposed on the black one, and is a mirror image of it.

In Unit 24 we also noted the symmetry of the ocean ridges; not only in their topography but also in their magnetic properties. The symmetry of magnetic anomaly profiles across ocean ridges is remarkable, one side being an almost perfect mirror image of the other (Fig. 9).

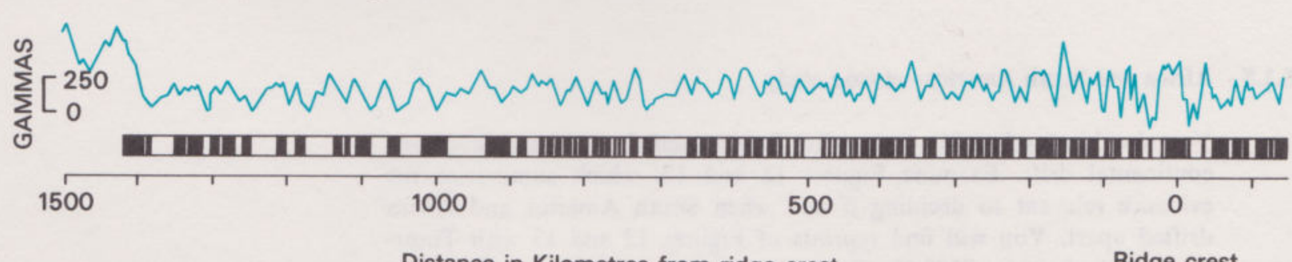
How are these anomalies formed?

It is suggested that new ocean-floor material is created by intrusion and extrusion of basalts along the median zones of oceanic ridges. Figure 10 (a) shows the magnetic anomaly profile across part of the South Atlantic ocean ridge. The fluctuations in the magnetic field have been simplified in the strip shown in the lower half of the Figure, so that lows are shown in black, and highs in white. In Figure 10 (b), the anomaly from the ridge 100 km west of 10 (a) has been turned on end and placed beside the magnetic polarity time scale described in Unit 23.

How do they compare?

They compare so well that it is now accepted that the magnetic anomalies were produced by successive field reversals as ocean floor material was extruded. Because this new material is extruded at the same rate on both sides of the ridge, the magnetic anomalies on each side are the same, thereby accounting for the symmetrical profiles.

(*a*)



(*b*)

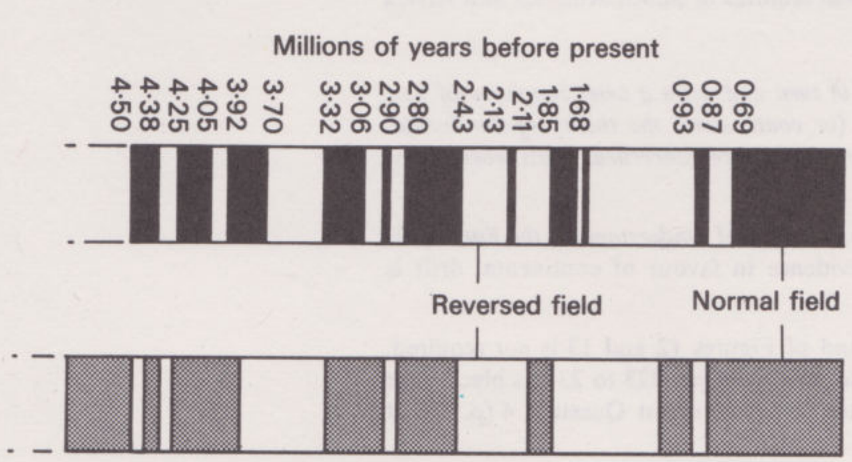


Figure 10

(*a*) *Magnetic anomaly profile for western half of South Atlantic, with ridge crest on the right: underneath the profile, positive anomalies are shown as black bars, negative ones are white.*

(*b*) *Comparison of the ridge crest profile shown in A with the polarity reversal time scale deduced from continental rocks.*

Matching the magnetic anomaly pattern and the polarity time scale in Figure 10 b shows that 70 km of ocean floor has been extruded on the west side of the oceanic ridge during the last 3.5 Ma. From this data, calculate the rate of sea-floor spreading per year for the South Atlantic.

The spreading rate is approximately 2 cm per year per ridge flank. This means that the Atlantic is growing in width at a rate of 4 cm per year, 2 cm per year being added to each ocean ridge flank. So, if we assume a constant spreading rate, we can use the oceanic magnetic anomalies to date the ocean floor. The South Atlantic is commonly used as a 'standard' with which to compare all other ocean anomalies. By assuming a constant spreading rate for the South Atlantic, variations in the rates of spreading for other oceans relative to the standard can be detected. This is shown in Figure 11.

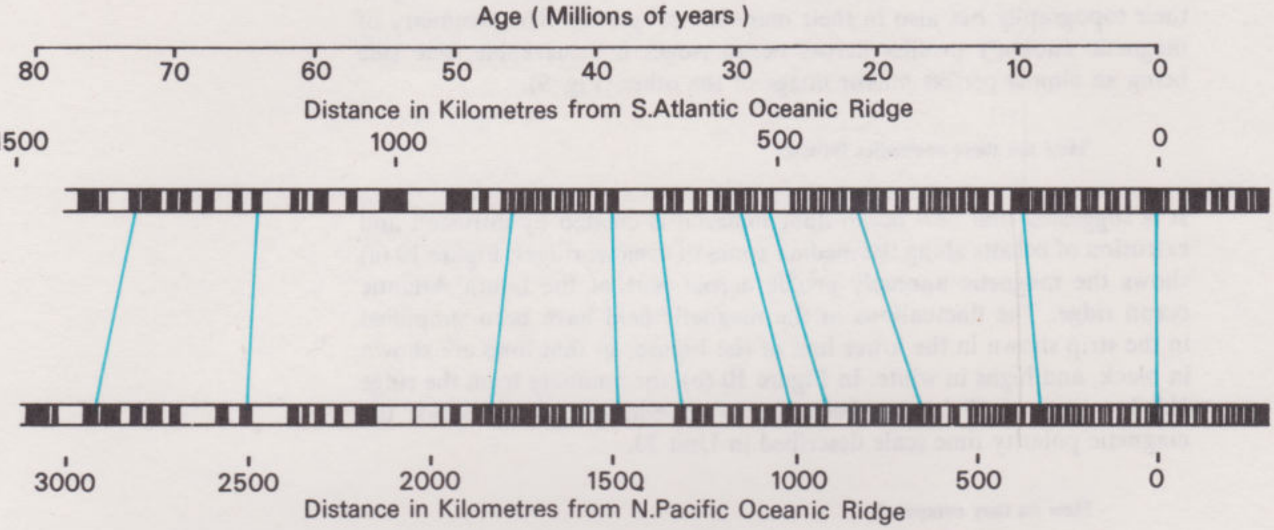


Figure 11 *Variation in spreading rates between south Atlantic and north Pacific, assuming a constant rate for the former. Coloured lines correlate between the two oceans, and show variations in the spreading rate between them. For example, between* 10 *and* 20 *Ma ago, the south Atlantic spread (on its west side) nearly* 200 *km, but the north Pacific spread by half as much again.*

25.1.5 Africa and South America—a case study

You should now be able to evaluate for yourself the evidence favouring continental drift. Examine Figures 12 and 13, which summarize the evidence relevant to deciding if and when South America and Africa drifted apart. You will find reprints of Figures 12 and 13 with Tutor-Marked Assignment S100 08. The outlines can be cut out and placed side by side to show how the geological features of South America and Africa fit together.

Consider each piece of evidence in turn and write a brief summary of how you think the evidence supports (or contradicts) the theory of continental drift as far as South America and Africa are concerned. (This work forms part of TMA S 100 08.)

You may also like to consult pp. 212–223 of *Understanding the Earth* (this is white-page reading), where evidence in favour of continental drift is reviewed.

Factual recall of this material and of Figures 12 and 13 is *not* required. If you wish, you may continue to read from pp. 223 to 231 as black-page reading. You may also like to try Self-Assessment Question 4 (p. 30) at this stage.

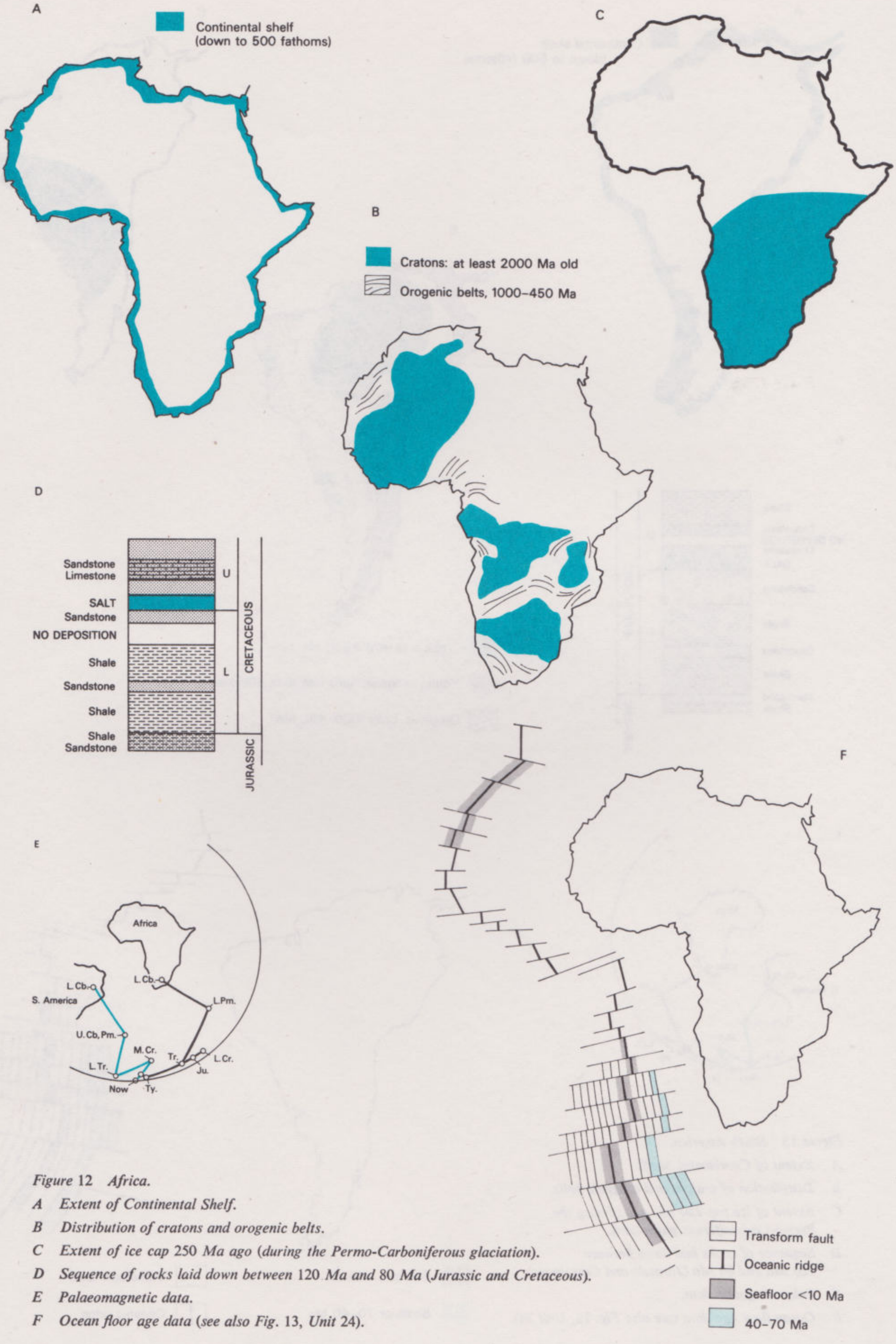


Figure 12 *Africa.*

A Extent of Continental Shelf.

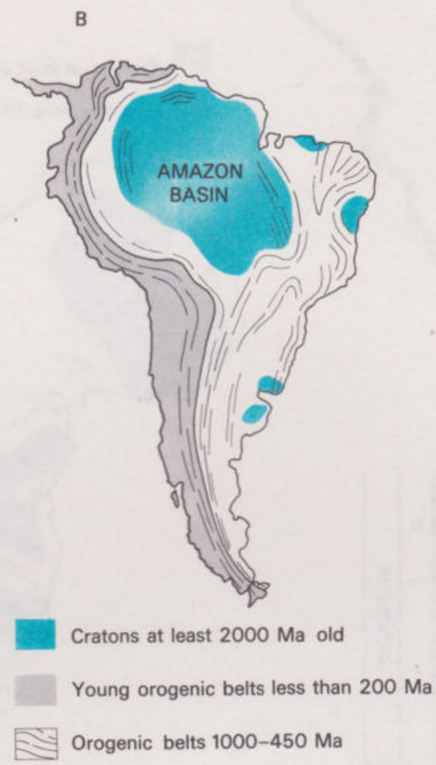
B Distribution of cratons and orogenic belts.

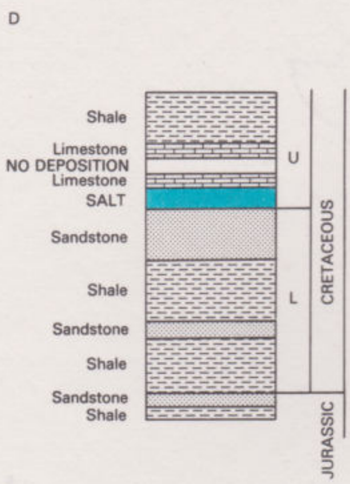
C Extent of ice cap 250 *Ma ago (during the Permo-Carboniferous glaciation).*

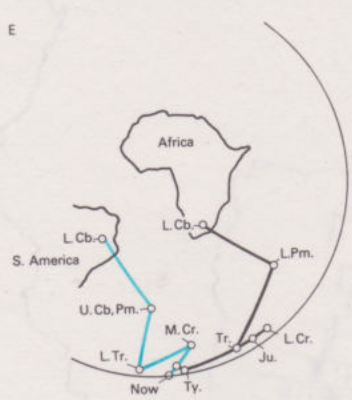
D Sequence of rocks laid down between 120 *Ma and* 80 *Ma (Jurassic and Cretaceous).*

E Palaeomagnetic data.

F Ocean floor age data (see also Fig. 13, *Unit* 24).







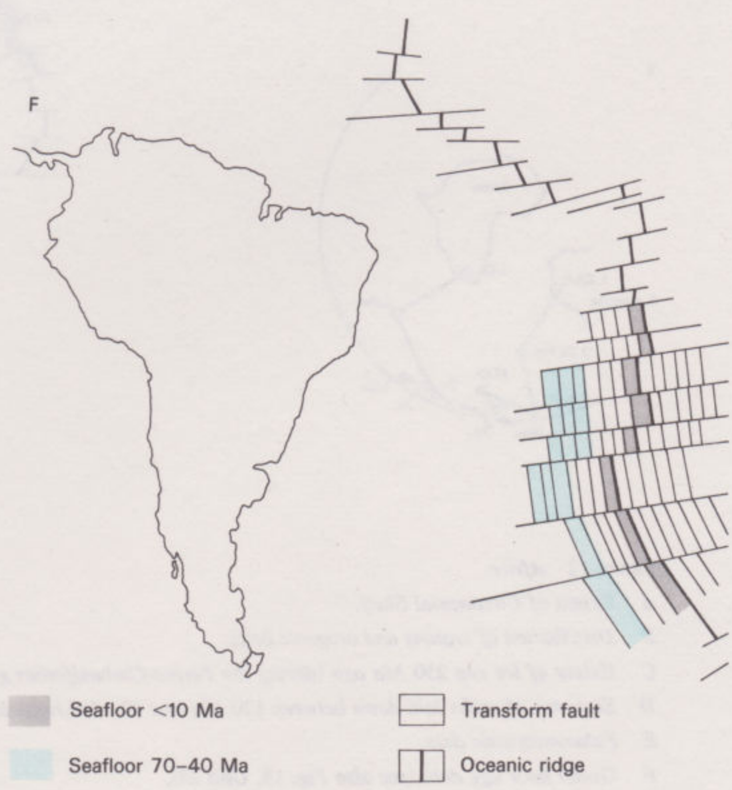


Figure 13 *South America.*

A Extent of Continental Shelf.

B Distribution of cratons and orogenic belts.

C Extent of ice cap 250 Ma ago (during the Permo-Carboniferous glaciation).

D Sequence of rocks laid down between 120 Ma and 80 Ma (Jurassic and Cretaceous).

E Palaeomagnetic data.

F Ocean floor age data (see also Fig. 13, *Unit* 24).

25.2 Sea-Floor Spreading and Plate Tectonics

25.2.1 Sea-floor spreading and the birth of the plate tectonics theory

You have already been introduced to the theory of sea-floor spreading. Chapter 16 of *Understanding the Earth* is written by Dr. F. J. Vine, one of the originators of the idea, who traces its development, explains it in some detail, and introduces the theory of plate tectonics, which we shall take up again later in this Unit. As you will see, the work of Dr. Vine and his contemporaries has revolutionized our understanding of the Earth. This 'revolution' will be discussed in the radio programme of Unit 25.

Now read Chapter 16, *and then return to this part of the text* (*note that there will be some overlap between the content of this chapter and the rest of the text. We hope that this will help you to a better understanding of some of the more difficult concepts.*) Some of the terms in this chapter with which you may be unfamiliar are explained in the glossary (Appendix 1) at the end of this Unit (p. 28).

In this Unit, we have brought evidence to demonstrate that the continents have moved about the face of the Earth through geological time, and that most of the present-day ocean floor has been created in the last five per cent of geologic time. The discussion has been largely concerned with direct and indirect observations. Like all other scientists, Earth scientists try to unify their observations to produce an all-embracing theory. In this case it is a theory in which features of the Earth's surface are envisaged as being produced by the interaction of a series of plates of crustal material which have moved about the Earth's surface. Such a theory is briefly described in the final pages of Chapter 16 and in more detail by Dr. Oxburgh in Chapter 19 of *Understanding the Earth*, to which we shall refer you later in this section.

The idea that the outer crust of the Earth consists of a small number of moving plates is a simple unifying concept which appears to explain the form and distribution of the Earth's surface features, such as continents, oceans, oceanic ridges and troughs, earthquake belts and volcanoes.

25.2.2 The plates

Do you recall (Unit 22) that earthquakes are produced when the outer part of the Earth fractures in response to strain? From the nature of the waves emitted, it is possible to tell the direction in which the outer part of the Earth moved to cause the strain. The time at which the earthquake occurred and the extent and direction of movement can also be deduced. However, seismology is a young science and has become truly quantitative only in the very recent past. A plot of the foci of earthquakes that have occurred during the ten years 1960–1970 shows a very interesting pattern.

Examine Figure 16.1 of *Understanding the Earth*. Do you notice any pattern?

Virtually all the earthquakes during this period have occurred within well-defined belts called *seismic zones* (see Unit 22). This pattern can be taken back on less precise instrumental records for about 70 years, and on imprecise historical records for another 2 000 years. In all cases the same pattern emerges.

On seismological evidence, we can subdivide the Earth's surface into large areas that rarely have earthquakes, known as *aseismic plates*, separated by narrow seismic zones where earthquakes are common.

Can you pick out the six aseismic plates from Figure 16.1 in *Understanding the Earth*? If not, look at Figure 16.13 where the six major aseismic plates are named.

From these figures you can see that a plate can be largely continental, (the Eurasian plate), largely oceanic (the Pacific plate), or both continental and oceanic (the African and American plates). Some plate margins coincide with oceanic margins, others do not.

There are four main types of plate margin. The main features of these are summarized in Figure 6, and described below.

1 *Constructive or oceanic ridge margins*

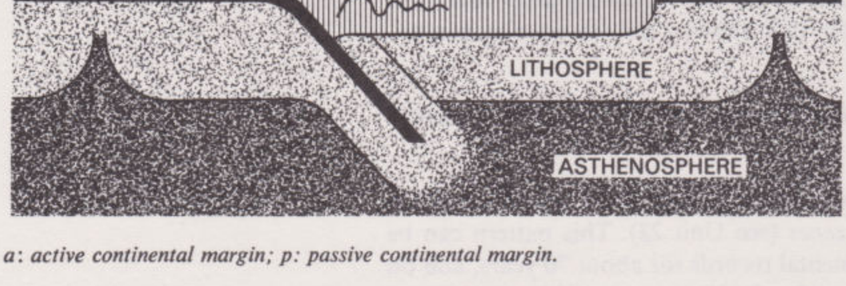
As described in section 25.1.4, new ocean floor is being created along the oceanic ridge crests. Data from the narrow zones of shallow earthquakes, which characterize the oceanic ridges, leaves little doubt that the segments of the sea floor on either side of the crests are moving apart. This being so there should be widening and deepening crack along the ridges—but there is not. So the space must be filled by new material brought up from below by volcanic activity. It appears that as two oceanic plates move apart, new molten rock material (magma) is injected into the gap, solidifying to basalt and thus enlarging the plates. Such margins are therefore known as constructive plate margins.

2 *Destructive margins of coastal mountain range and island arc type*

As it appears that new ocean floor has been continually created over the last 200 Ma, then it follows that somewhere the Earth's crust must be destroyed.

Where is this happening?

Let us consider a section through the Earth's crust extending from the South Atlantic westwards to the East Pacific Rise along 20° latitude in the southern hemisphere (see Fig. 14 and 16.13 in *Understanding the Earth*). New ocean floor is generated at the Mid-Atlantic Ridge, so that the western South Atlantic and South America, both part of the same aseismic plate, are moving westwards relative to the Mid-Atlantic Ridge.



a: active continental margin; p: passive continental margin.

Figure 14 Simplified section from East Pacific Rise across East Pacific—S. America—South Atlantic to the Mid-Atlantic ridge.

At the same time, new ocean floor generated at the East Pacific Rise is moving eastwards relative to the Rise. It seems that these two plates must be meeting head-on.

Can you think what might happen?

Oceanic crust apparently plunges down beneath the continental plate to be resorbed by the mantle. This theory is supported by the disposition and first motion directions of the earthquake foci in the broad, inclined seismic zone beneath the western seaboard of South America. So, along this broad seismic (Benioff) zone (and along similar ones all round the Pacific) the ocean floor is disappearing, being consumed as it plunges downwards into the Earth's mantle. On the upper surface of this sloping plate of oceanic crust, there are numerous earthquakes, shallow ones near the coast, deepening inland to as much as 700 km. Recently, there has been confirmation of the sinking of this plate by the discovery that seismic waves originating from deep earthquakes on the plate travel faster up the plate than they do in other directions. This is a clear indication that the waves are travelling more quickly through the cold rigid oceanic plate than through the surrounding mantle, which is hot and has lower coefficients of rigidity and compressibility (see Unit 22).

Commonly, where the oceanic plate plunges down into the mantle, there is an oceanic trench characterized by large negative gravity anomalies such as those usually found around the margins of the Pacific (Unit 24, Fig. 38). The fact that some of these trenches are empty is explained by this process, for it is entirely acceptable that, as the plate descends, it takes with it some of the sediments in the trench. The rest of the sediment seems to be scraped off against the leading edge of the advancing continental plate, to be incorporated later into an adjacent mountain chain.

The meeting of the two plates produces crustal deformation due to compression, resulting in the formation of an orogenic belt, in this case the Andes mountains along the west coast of South America, which contains numerous volcanoes. In the Andes, the lavas extruded from these volcanoes are richer in silica than is basalt, and it is suggested that they could be formed by partial melting of the descending oceanic plate and its overlying sedimentary cover as the plate reaches depths of around 150 km. Here, the mantle temperature is high enough to promote partial fusion. The descending ocean floor is therefore destroyed, and in the process gives rise to volcanic activity.

We have discussed what happens when plate movement causes oceanic crust to impinge on continental crust along a plate margin. Destructive margins also develop between adjacent oceanic plates. A good example occurs along the margins between the Philippine and Pacific plates (see Figure 16.13 of *Understanding the Earth*). Along this margin, part of the western edge of the Pacific plate plunges down along a line marked by the Philippine trench (Unit 24, Fig. 38). Volcanic activity associated with this plate descent has produced the chain of volcanic islands known as the Philippine island arc (Fig. 15). Island arc and trench systems are characterized by high gravity anomalies which are positive over the islands (see Unit 24, section 24.3.4 example 2) and negative over the trenches.

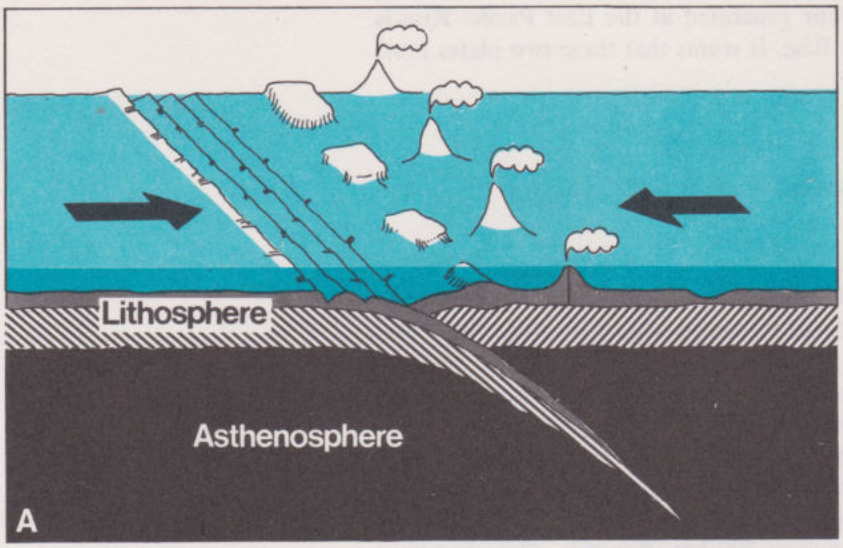


Figure 15 Section of the Earth's crust showing active type of plate margin, with oceanic lithosphere plunging beneath continent, producing an inclined plane of earthquake activity and an orogenic belt with volcanic activity on the continent.

3 *Destructive margins of intracontinental type*

Consider Figure 16 (a), where two continental blocks are moving together as ocean floor between them is being destroyed. When all the ocean floor has disappeared, the two continents will meet. Neither can return to the mantle because of the buoyancy of these lower density plates (continental crust density 2 700 kg m^{-3}, oceanic crust 3 000 kg m^{-3}), so there will be a collision (Fig. 16 (b)). The sediments accumulated on the continental margins will be compressed, folded, and uplifted to form a mountain range. The best example of this is a collision, thought to be still in progress, between the Indian subcontinent and the rest of southern Asia to the north, resulting in the formation and uplift of the Himalayan orogenic belt. The oceanic crust which once separated these two continental plates has been completely destroyed.

(*a*)

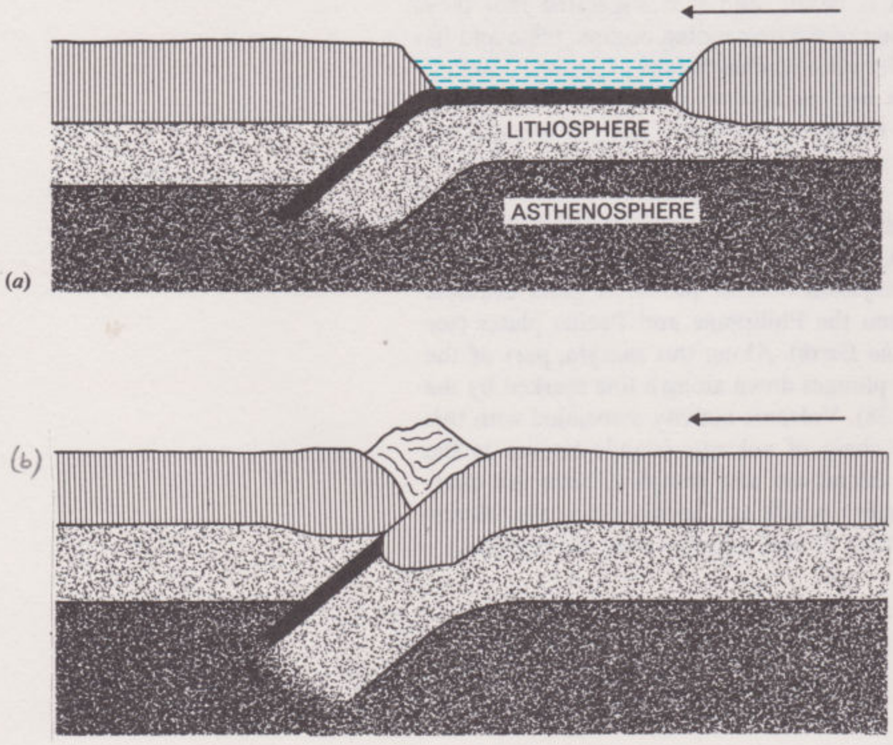


Figure 16 Collision of two continental blocks. Further explanation in the text.

4 *Conservative margins*

These are margins along which plates slide past each other neither gaining nor losing material. The Great San Andreas fault line along the western seaboard of the USA is a good example. Like all such margins, this is a great transform fault (see Unit 24, Appendix 3) along which the north-eastern part of the Pacific plate is moving north-westwards relative to the American plate. The fault ends at Alaska where this part of the Pacific plate descends beneath the Aleutian island arc (Fig. 16.13 in *Understanding the Earth*).

Now see if you can select from the array below, the features which characterize the *first three types of margin listed.* To do this you may like to refer back to the following sources:

Understanding the Earth: pp. 245–8, Figures 16.1, 16.2 and 16.13. Unit 24: sections 24.3, 24.4.6, 24.4.7, Appendix 2, and Figures 9 and 39.

Put ticks in the blank arrays to indicate your choice of features for each type of margin, and then check your answers against those tabulated on p. 24.

Type 1

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Type 2

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

Type 3

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

1 Positive gravity anomaly	**2** Basaltic volcanic activity	**3** Narrow zone of shallow focus earthquakes	**4** Oceanic: oceanic plate junction
5 Island arcs	**6** Junction along relatively young orogenic belt	**7** Tensional features in crust	**8** Plate destruction
9 Negative gravity anomaly	**10** Broad seismic zone with earth-quake foci lying along an inclined plane	**11** Oceanic: continental plate junction	**12** Compressional features in the crust
13 Plate construction	**14** Shallow and intermediate earthquake focus zone	**15** Ocean trenches	**16** Continental: continental plate junction

Answers to the problem on p. 23

Type 1

1	2 ✓	3 ✓	4 ✓
5	6	7 ✓	8
9	10	11	12
13 ✓	14	15	16

Constructive or oceanic margins

Oceanic/Oceanic

Type 2

1 ✓	2	3	4 ✓
5 ✓	6 ✓	7	8 ✓
9 ✓	10 ✓	11 ✓	12 ✓
13	14	15 ✓	16

Oceanic/Continental
or Oceanic/Oceanic

Type 3

1 ✓	2	3	4
5	6 ✓	7	8 ✓
9	10	11	12 ✓
13	14 ✓	15	16 ✓

Destructive margins

Continental/Continental

25.2.3 Summary of section 25.2.2

In the last section, we have been describing a process which seems to explain the majority of the Earth's surface features—why the continents are so old, why the ocean basins are so young, why the earthquake belts occur where they do, and why volcanoes occur in definite zones. However, the details are by no means certain and there is still a great deal of work to be done before the entire picture is unravelled.

There are four major points to remember about the plate tectonics theory:

1 the outer part of the Earth's surface is divided into six or possibly seven major plates and at least fifteen minor ones;

2 the plates move as rigid bodies, and are only deformed where their relative motion causes impingement or collision;

3 the oceanic plates are destroyed at the oceanic trenches by plunging down into the mantle, where finally they are remelted to mix again with the mantle from whence they came;

4 destruction is compensated by the creation of new plate material along oceanic ridges. The process is continuous and is analogous in many ways to a conveyor belt in mass production. Ocean floor, created at the oceanic ridges, travels outwards, receiving as it does so a veneer of sediments. Where oceanic crust is forced down into the mantle it is destroyed, but part of it is geologically reborn as new continental crust in the form of silica-rich lavas extruded by the volcanoes in the mountain chains and island arcs.

25.2.4 Causes of plate motion

We have indicated in a qualitative way the likely directions of plate motion. More quantitative information is obtained by considering the nature of earthquake waves propagated by crustal displacement along faults. (Refer to Unit 22, where the method of determining the direction of first motion along faults is discussed. Also read pp. 269–272 of Chapter 19 in *Understanding the Earth*, which shows how the first motions deduced for earthquakes occurring along plate boundaries are consistent with movements predicted by the theory of plate tectonics.)

Up to now we have described plate movement without attempting to describe the mechanism which causes it. It is extremely difficult to find such a mechanism, because we are attempting to investigate something not only physically remote—buried deep in the Earth—but also remote in terms of its vast scale and the period of time during which it must have operated.

You will remember (Unit 22) that on seismic evidence we subdivided the upper part of the Earth into the outer crust, separated from the underlying mantle by the Mohorovičić discontinuity. In the upper mantle there is a zone, extending from a depth of about 100 km below the Earth's surface to a depth of about 400 km, where seismic waves travel more slowly. This is called the seismic low-velocity layer. In Unit 22 and Chapter 19 of *Understanding the Earth*, it was suggested that in this layer the material of the Earth's mantle is sufficiently close to its melting temperature for about 5 per cent of it to be molten. The liquid occurs as a dispersed phase throughout the layer.

This gives a zone known as the asthenosphere or rheosphere which is inherently weak. If the outer part of the Earth moves with respect to the inner part, then it may well do so along this layer. It is the outer part of the Earth (the lithosphere), incorporating both the crust and the uppermost part of the mantle, which forms the moving aseismic plates. The plates appear to be passive passengers, and the driving mechanism for their movement must therefore be located either in the asthenosphere or even deeper in the Earth. Various theoretical models have been constructed for this driving mechanism, based on attempted calculations of the rigidity, compressibility and plasticity of the Earth's interior.

The simplest model, proposed many years ago by the doyen of British contemporary geology Arthur Holmes, likened the Earth to a pan of cooling water in which convection currents have developed. The hotter water rises in the centre of the pan, spreads out at the surface, cools and descends down the sides of the pan. Likewise, the model suggests that within the Earth there are huge convection currents rising under the oceanic ridges and descending under the active plate margins, as shown in Figure 17 A (compare Fig. 16.3 in *Understanding the Earth*).

Subsequent recognition of the asthenosphere layer in the upper mantle made this model untenable. Convection on the scale shown in Figure 17 A could not proceed without totally disrupting such a layer. Also, solid state physicists have recently calculated the properties of the deep mantle to be such that convection as understood in the laboratory situation would be impossible, the lower part of the mantle (below the asthenosphere) is too rigid for flow in this sense to occur.

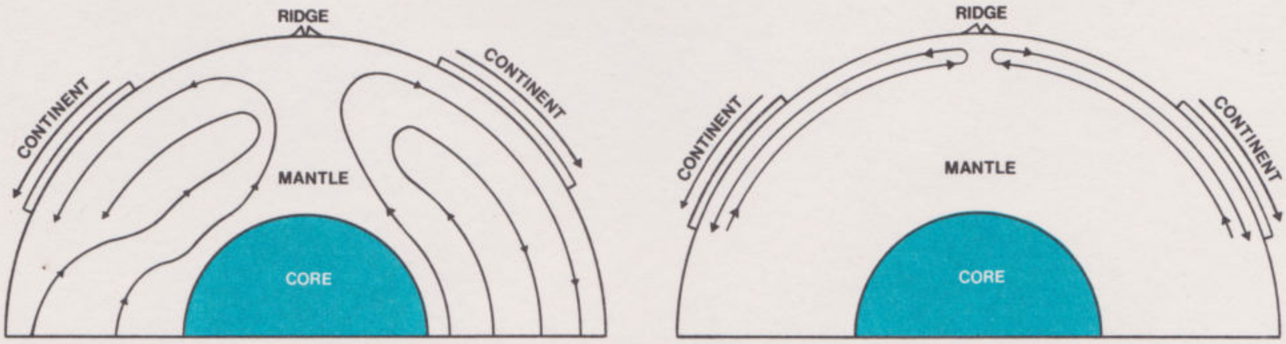


Figure 17

A Convection current hypothesis (involving the mantle) to account for the occurrence of oceanic ridges and orogenic belts.

B Modified convection current hypothesis involving long flat convection cells.

It has therefore been suggested that the convection may take place within the thin layer of the asthenosphere, between 100 and 400 km deep (Fig. 17 B). On this model we have pancake-like convection cells, again rising under the oceanic ridges but with the return current coming back only a few hundred kilometers below the outward-spreading, upper current. This model is also unsatisfactory to some investigators, because the outward-spreading upper current would, they suggest, interfere with the returning lower current, so that the flat convection cell would be broken up into a series of smaller convection cells.

The whole problem really depends on just how fluid the asthenosphere really is. What is its plasticity? Does it have the 'stiffness' of treacle or of tar? Is it easily deformed? At one extreme, some suggest the layer to be so well lubricated that, when a continental plate is ruptured and basaltic material is intruded into the lithosphere from the asthenosphere below, the mere injection of this new oceanic material causes the flanking continents to 'roll apart'. Another suggestion, compatible with this idea, is that as the ocean floor is highest at the oceanic ridge axis, such a movement would be helped by the rigid plates sliding away from either side of the ridge simply under the influence of gravity.

At the other extreme, some believe that the destructive zone where the cold lithospheric plate descends into the mantle is where the convective 'engine' operates. The theory here is that the cold lithospheric plate, being denser and therefore heavier than the warm underlying mantle, will sink even deeper under its own weight, pulling the rest of the plate with it. If this subject particularly interests you, we would refer you to the remainder of Chapter 19 in *Understanding the Earth*, which treats in greater detail the problems outlined here. *This Chapter* (*p.* 273 *onwards*) *is black-page material.*

Summary

There are five categories of evidence in support of the theory of continental drift: (1) topographic fit of the continental shelves; (2) match of orogenic belts between continents when restored to pre-drift positions; (3) match of palaeoclimates, palaeofauna and flora, *and* palaeogeographies between continents; (4) match of polar wandering curves between continents for periods prior to break-up; and (5) ocean floor evidence for 'sea-floor spreading'.

Magnetic anomaly profiles across ocean ridges are symmetrical, and may be matched with the geomagnetic polarity time scale obtained by radiometric dating of lava sequences on land. Such methods are used to date the ocean floor and the results have been confirmed by radiometric and palaeontologic dating of samples recovered from the ocean floor.

The pattern of crustal movement indicated by 'sea-floor spreading' fits satisfactorily with crustal movements deduced from the investigation of earthquake first motion directions. The pattern of movement is explained by postulating the Earth's crust to be a series of 'rigid' plates—this theory is termed 'plate tectonics'. The underlying causal mechanism is as yet obscure, although it is likely that convective movements in the Earth's mantle may be responsible.

Further Reading

I. G. Gass, P. J. Smith and R. C. L. Wilson (*Eds.*), *Understanding the Earth*. Artemis Press, 1971, Chapter 19.

C. R. Longwell, R. F. Flint and J. Sanders, *Physical Geology*. Wiley, 1969, Chapter 22.

Arthur Holmes, *Principles of Physical Geology*. Nelson, 1965, Chapter 28.

This material is 'pre-plate tectonics' but describes convection theories for crustal movement.

Sir Edward Bullard, 'The Origin of the Oceans' and H. W. Menard, 'The Deep Ocean Floor', *Scientific American*, special issue, September 1969. (Reprint Nos. 880 and 883). Also available in book form, *The Ocean*, W. H. Freeman and Co., 1969.

Glossary

Unit 25

EVAPORITE Sediment formed by precipitation of minerals from sea water.

GLACIER Moving mass of ice and rock debris.

ISOBAR Line joining points of equal atmospheric pressure.

POLAR WANDERING CURVE The line produced by joining successive palaeomagnetic pole positions (as measured in a stratigraphic succession for one continent) through time (see Fig. 15.10 in *Understanding the Earth*).

TILLITE Poorly sorted sedimentary rock deposited from melting ice.

Chapter 16, *Understanding the Earth*

CHERT A compact siliceous rock of organic or precipitated origin.

DOLERITE Rock produced by basaltic volcanism.

DYKE A vertical to sub-vertical sheet-like body of intrusive igneous rock.

DYKE SWARM A set of parallel to sub-parallel dykes.

FISSION TRACK DATING Method of radiometric dating.

GEOTHERMAL GRADIENT The change in temperature of the Earth with depth.

GEOTHERMS Surfaces of equal temperature within the Earth.

MARINE TRANSGRESSION Gradual expansion of a shallow sea resulting in the progressive submergence of land, either by a rise in sea level, or land subsidence.

PELAGIC SEDIMENTATION Deep sea sedimentation.

POTASSIUM-ARGON DATING Method of radiometric dating.

RADIOGENIC DATE Radiometric date.

REFLECTING HORIZON Subsurface layer which reflects seismic waves.

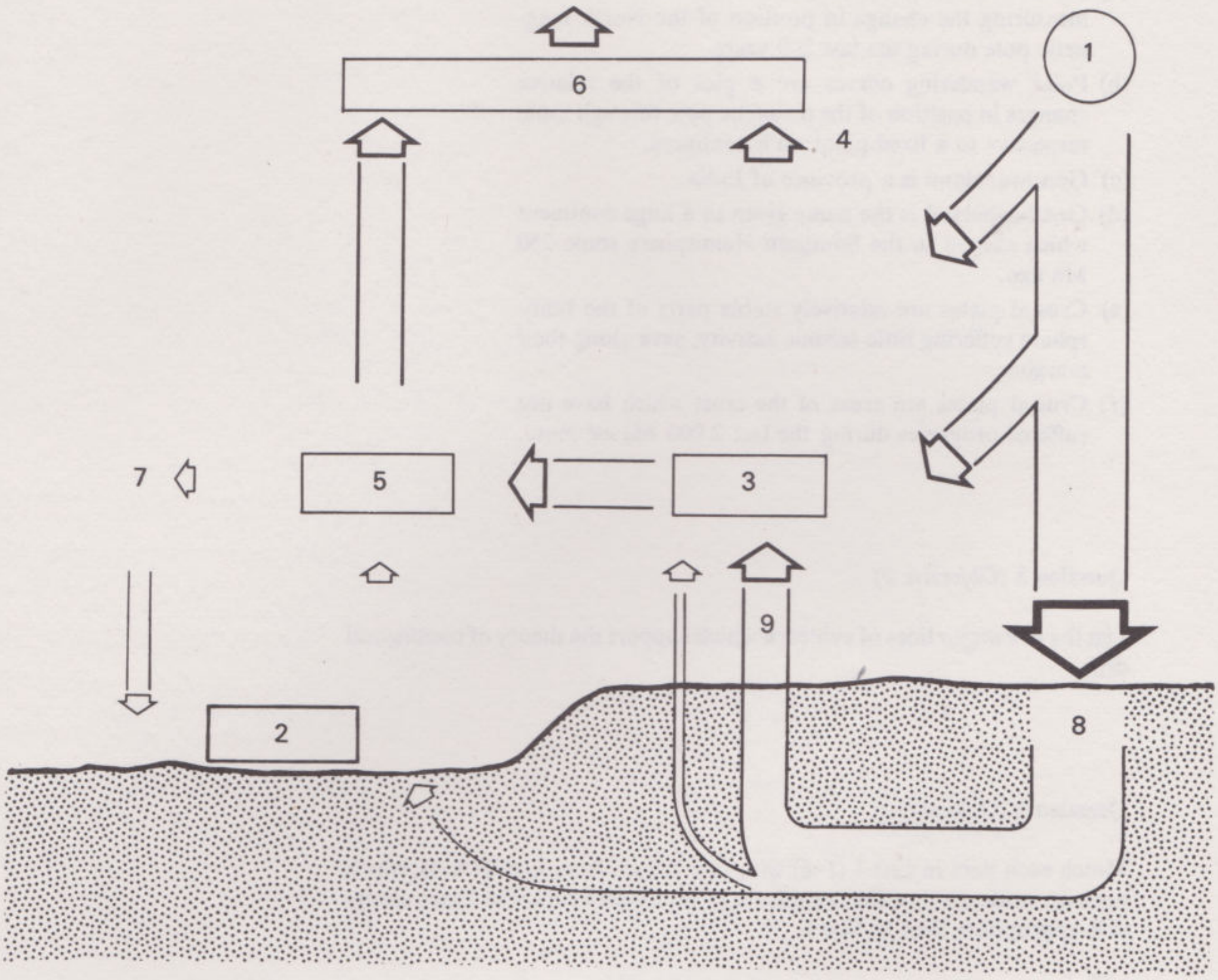
SCARP Escarpment.

STRIKE-SLIP DISPLACEMENTS Same as transcurrent faults (see Unit 24).

THOLEIITIC BASALT Rock produced by basaltic volcanism.

Self-Assessment Questions

Section 1



Question 1 (*Objective 1*)

Match the items (a–i) listed below with the numbers (1–9) on the diagram to show the energy flow of the atmosphere; place the appropriate number alongside each item.

Number

(a) Solar energy

(b) Absorption by the Earth

(c) Wind

(d) Heat content of atmosphere

(e) Terrestrial radiation

(f) Ocean currents

(g) Latent heat (water vapour)

(h) Reflection by clouds, etc.

(i) Absorption by atmosphere

Question 2 (*Objective 1*)

Indicate whether the following statements are true or false.

	True	*False*
(a) Polar wandering curves have been constructed by measuring the change in position of the North magnetic pole during the last 200 years.		
(b) Polar wandering curves are a plot of the relative changes in position of the magnetic pole through time, respective to a fixed point on a continent.		
(c) Gondwanaland is a province of India.		
(d) Gondwanaland is the name given to a huge continent which existed in the Southern Hemisphere some 250 Ma ago.		
(e) Crustal plates are relatively stable parts of the lithosphere suffering little seismic activity, save along their margins.		
(f) Crustal plates are areas of the crust which have not suffered orogenies during the last 2 000 Ma or more.		

Question 3 (*Objective 2*)

List the five major lines of evidence which support the theory of continental drift.

Question 4 (*Objective 2*)

Match each item in List 1 (1–6) with one chosen from List 2 (A–I), which presents evidence that the continents have drifted apart. Put letter alongside appropriate item in List 1.

LIST 1

1 Palaeomagnetic evidence
2 Topographic fit
3 Match of orogenic belts
4 Precision of glacial evidence
5 Comparison of stratigraphy between continents
6 Climatic belts

LIST 2

A In sedimentary basins along Atlantic margins of Africa and South America, the rocks formed during the Triassic and Jurassic periods are very similar to each other, and contain freshwater fossils. In the Lower Cretaceous, evaporites formed in all the basins, but younger deposits cannot be so well matched across the present-day Atlantic, for they contain relatively dissimilar marine fossils.

B In both Africa and South America, the geological record indicates that each continent experienced similar climatic conditions at approximately the same time for the past 600 Ma at least.

C Computer analyses have shown that the 500 fathom line gives the best fit between Africa and South America, the average misfit being about 90 kilometres.

D Palaeomagnetic evidence enables the co-ordinates of Africa and South America to be located for a period some 200 Ma ago, thus proving that the two continents were once in juxtaposition.

E The match between the coastlines of South America and Africa is fairly good, but the present-day coastline does not truly reflect the position of the continental margin.

F As the limit of an ice sheet is governed by the phase change from ice to water, the geological record left behind by such conditions is temperature controlled. Fortunately the limit of the Permo-Carboniferous ice sheet in Africa and South America can be mapped: when these continents are brought together, the match between the ice sheets is remarkably good.

G Ancient mountain chains are often truncated by coastlines and have not been found to continue across the ocean floors. However, when the continents are reassembled into their pre-drift positions, it is found that these mountain belts often continue across the join.

H Climatic belts at the present time are roughly parallel to lines of latitude; so Africa and South America are today experiencing similar climates. Thus, broad similarities between rock successions does not necessarily favour their former juxtaposition. However, because in both South America and Africa, Permo-Carboniferous glacial deposits are followed by Triassic desert deposits, lateral movement of these continents from higher to lower latitudes must be favoured.

I Measurement of the remanent magnetism of rock can find the palaeolatitude only for a particular geological period (see Unit 23). Thus, in one sense, the continent is only 'fixed' in a manner similar to that given by palaeoclimatic indicators. However, the palaeopole position can be located as a 'point', within a margin of error (see latter half of TV Unit 24). If a succession of rocks is available for palaeomagnetic analysis, a polar wandering curve can be constructed. In the case of Africa and South America, the curves for each continent coincide during the Carboniferous, Permian and Triassic, but by the Cretaceous they began to diverge and continued to do so up to the present time.

Question 5 (*Objective 3*)

The large-scale circulatory pattern of the Earth's atmosphere is controlled by (indicate whether true or false):

	True	*False*
(a) seasonal changes in cloud cover modifying the balance between incoming and outgoing radiation;		
(b) convection set up between warmer equatorial regions and cooler polar regions;		
(c) modification of a simple double convection cell by the Coriolis force;		
(d) the distribution of Earth's internal heat.		

Question 6 (*Objective 3*)

Examine the four sketches, which show isobars and wind directions of high or low pressure areas in either the northern or the southern hemispheres. Cross out labels which are NOT correct.

A

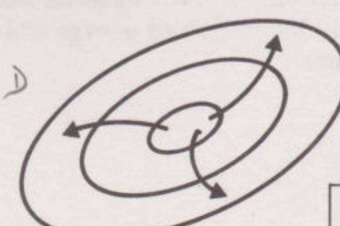
HIGH	LOW
NORTH	SOUTH

C

HIGH	LOW
NORTH	SOUTH

B

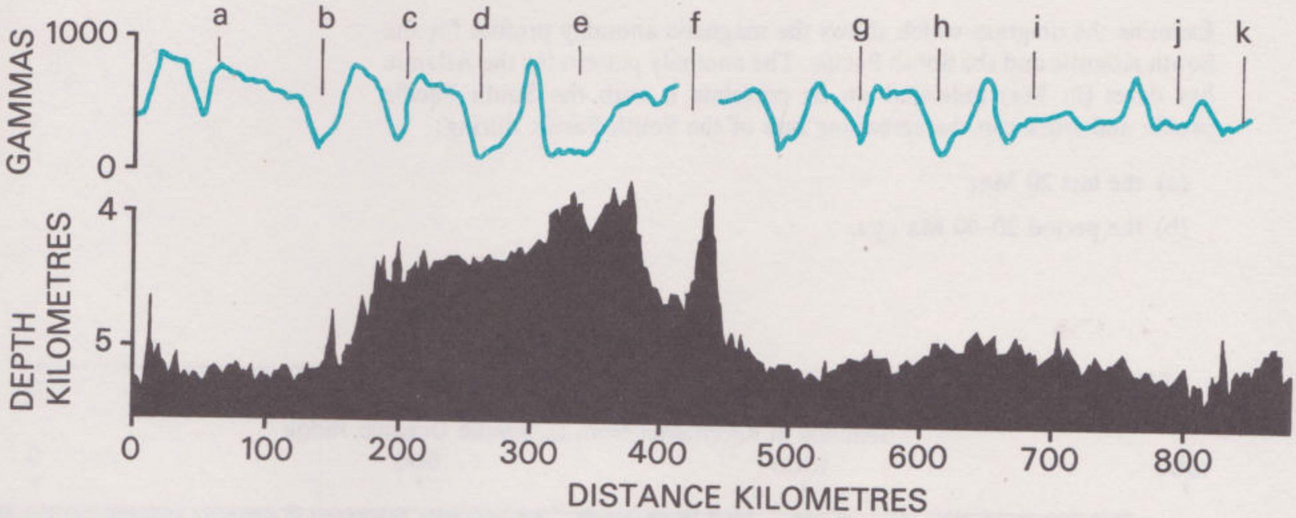
HIGH	LOW
NORTH	SOUTH



D

HIGH	LOW
NORTH	SOUTH

Question 7 (*Objective 5*)



Examine the illustration, which shows the topographic profile of an ocean floor, together with the magnetic anomaly profile. The anomalies are arbitrarily labelled from left to right. How would you interpret this information? Indicate whether the possibilites given below are likely to be true or false.

	True	*False*
(a) The topography suggests the traverse was made across an oceanic ridge.		
(b) The anomaly profile from a, b, c, d to e is a mirror image of that from f, g, h, i to j, thus confirming the view that the topography is characteristic of an oceanic ridge.		
(c) Anomalies b, c, d and e are the same as f, g, h and i respectively, suggesting a fault between e and f.		

Question 8 (*Objective 6*)

Examine the polar wandering curve for two hypothetical continents. When did they begin to drift apart?

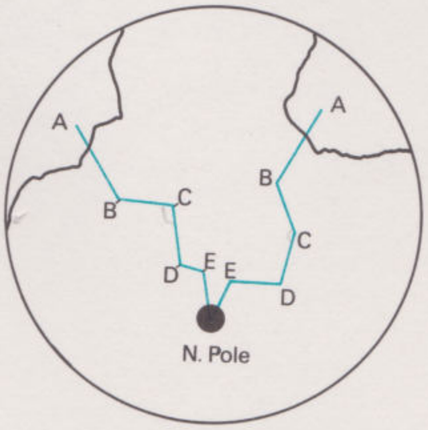
A 200 Ma

B 150 Ma

C 100 Ma

D 75 Ma

E 50 Ma

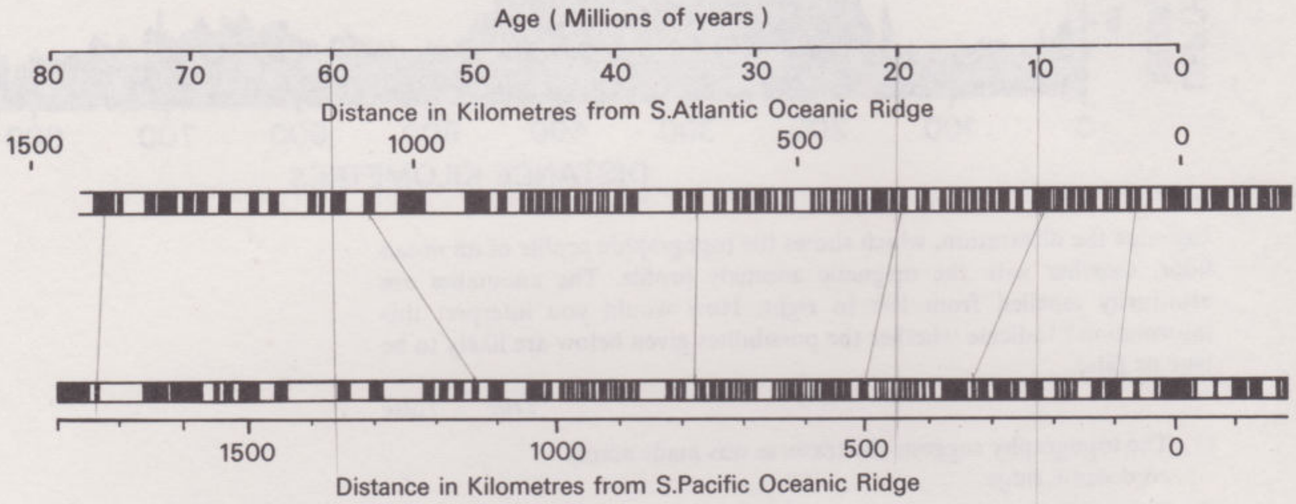


Question 9 (*Objective 6*)

Examine the diagram which shows the magnetic anomaly profiles for the South Atlantic and the South Pacific. The anomaly pattern for the Atlantic has dates (in Ma) indicated on it; correlate it with the South Pacific profile and work out the spreading rate of the South Pacific during:

(a) the last 20 Ma;

(b) the period 20–60 Ma ago.



Self-Assessment Questions

Section 2

Question 10 (*Objective 8*)

Write up to three short sentences summarizing how seismology has contributed to the formulation of the theory of 'Plate Tectonics'.

Question 11 (*Objective 9*)

Examine the Atlantic Floor Chart. Identify on it (using data from the Units and *Understanding the Earth*) *destructive* and *constructive* plate margins, and write down the names of topographic features along them.

Question 12 (*Objective 9*)

Constructive plate margins are (tick correct statement):

(a) regions where sediment is being deposited on continental slopes, thus building them out laterally over long periods of geological time;

(b) characterized by large fractures in the Earth's crust;

(c) regions where new crust is created.

Question 13 (*Objective 9*)

Destructive plate margins are (tick correct statement):

(a) characterized by ocean trenches, orogenic belts, and an inclined zone of earthquakes;

(b) characterized by folds and thrust faults;

(c) characterized by a narrow zone of shallow focus earthquakes.

Question 14 (*Objective 9*)

Continental crust is not destroyed at destructive plate margins because (tick correct statement):

(a) its compressibility and rigidity is such that it cannot be resorbed by the mantle;

(b) it is less dense than the mantle, and so cannot be thrust down into it;

(c) it has a melting point higher than the mantle.

Question 15 (*Objective 9*)

Conservative plate margins (tick correct statement):

(a) move slowly and resist change in their shape;

(b) are plate margins along which no movement occurs;

(c) are regions along which plates slip by each other without any change in their surface area.

Question 16 (*Objective 1*)

The Benioff zone is (indicate whether each of the statements is true or false):

	True	*False*
(a) a layer within the mantle in which shear waves have a comparatively lower velocity;		
(b) a zone containing the deepest recorded earthquakes;		
(c) another name for the ring of ocean trenches around the margins of the Pacific;		
(d) a zone of earthquake epicentres, usually inclined at 45°;		
(e) expressed at the Earth's surface by ocean trenches and island arcs;		
(f) a zone where continental collision occurs;		
(g) a well-defined zone of volcanic activity along continental margins.		

Question 17 (*Objective 1*)

The low-velocity layer is (indicate true or false statements):

	True	*False*
(a) a layer of oceanic crust which has been thrust under continental crustal material;		
(b) another name for the asthenosphere;		
(c) a world-wide zone within the mantle along which the velocity of shear waves reaches a minimum;		
(d) a zone along which plate movement is relatively slow;		
(e) below the lithosphere;		
(f) mantle material probably modified by partial melting;		
(g) a layer along which plate movement may occur.		

Self-Assessment Answers and Comments

Question 1

(a) 1, (b) 8, (c) 7, (d) 5, (e) 6, (f) 2, (g) 9, (h) 4, (i) 3.

Question 2

(a) false, (b) true
(c) false, (d) true
(e) true, (f) false

Question 3

The five major lines of evidence supporting the theory of continental drift are as follows.

1 Topographic fit between continental shelves
2 Fit between orogenic belts
3 Fit of palaeoclimatic, palaeontological, and palaeogeographic evidence
4 Palaeomagnetic evidence
5 Ocean floor evidence

Question 4

You should have matched the following items:

1: I
2: C
3: G
4: F
5: A
6: H

There are *three* items you should *not* have included.

B is a true statement, as both continents have, and still do experience similar climatic conditions—after all, they are at the same latitude! But this does not favour continental drift argument.

D is incorrect, as palaeomagnetic investigations can only locate palaeolatitudes (one co-ordinate) and not palaeolongitudes.

E is a true statement, but as the present coastline does not truly reflect the position of the continental margin, this is not proof of continental drift having occured.

Question 5

(a) False; these changes are brought about by seasonal changes in the Earth's large-scale circulatory pattern which cause changes in the cloud cover.
(b) True.
(c) True.
(d) False; much too small to have any effect.

Question 6

Remember that due to the Coriolis force winds blow anti-clockwise around low pressure areas in the northern hemisphere, and in a clockwise direction in the southern hemisphere. Therefore the answers are:

A: high, north. B: low, south.

C: low, north. D: high, south.

Question 7

(a) False; remember that the topographic profile on one side of the ocean ridge crest is the mirror image of that on the other side. No such symmetry can be discerned on this profile.

(b) False; trace off the anomaly pattern on some thin paper, then turn the paper over and see if the anomaly pattern fits—it does not. Remember anomalies on either side of an oceanic ridge are mirror images of each other.

(c) True; try it with the tracing paper the right way round.

Question 8

Between C and D. The shape of the curves for the two continents is the same between A and C. You could superimpose them exactly on one another, which means that the two continents moved together as one unit relative to the pole. After C the curves begin to look different, suggesting that the continents began to split apart and move independently between 75 and 100 Ma ago.

Question 9

(a) Ocean 'spread' 550 km in 20 Ma, so spreading rate is:

$$\frac{550 \times 10^5 \text{ cm}}{20 \times 10^6 \text{ years}}$$

$= 2.75$ cm per year per ridge flank.

(b) Ocean 'spread' 700 km in 40 Ma (60–20 Ma); so spreading rate is

$$\frac{700 \times 10^5 \text{ cm}}{40 \times 10^6 \text{ years}}$$

$= 1.75$ cm per year per ridge flank.

Note: You may have slightly different figures, but you should be within 2.6–2.9 for (a), and within 1.7–1.9 for (b).

Question 10

You should have included the following.

1 Seismology has located the main belts of earthquake activity around the world.

2 Seismological techniques have determined the depths of earthquake epicentres; these are shallow along oceanic ridges, but intermediate to deep when associated with ocean trenches, in this case they are concentrated along the inclined Benioff zones.

3 Earthquake first motion directions may be deduced from seismic data; this has revealed the nature of transform faults, and the 'underthrusting' along the Benioff zones.

Question 11

Constructive plate margins: The Mid-Atlantic Ridge.

Destructive plate margins: The Antilles island arc and trench system. The Scotia island arc and trench system.

Question 12

c is correct.

Question 13

a is correct, b only partially.

Question 14

b is correct.

Question 15

c is correct.

Question 16

b, d, e, are correct.

You may have included g; this is associated with the Benioff zone, but not part of it.

Question 17

b, c, e, f are correct.

g may be correct—but we do not really know.

Acknowledgements

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UNIT 24

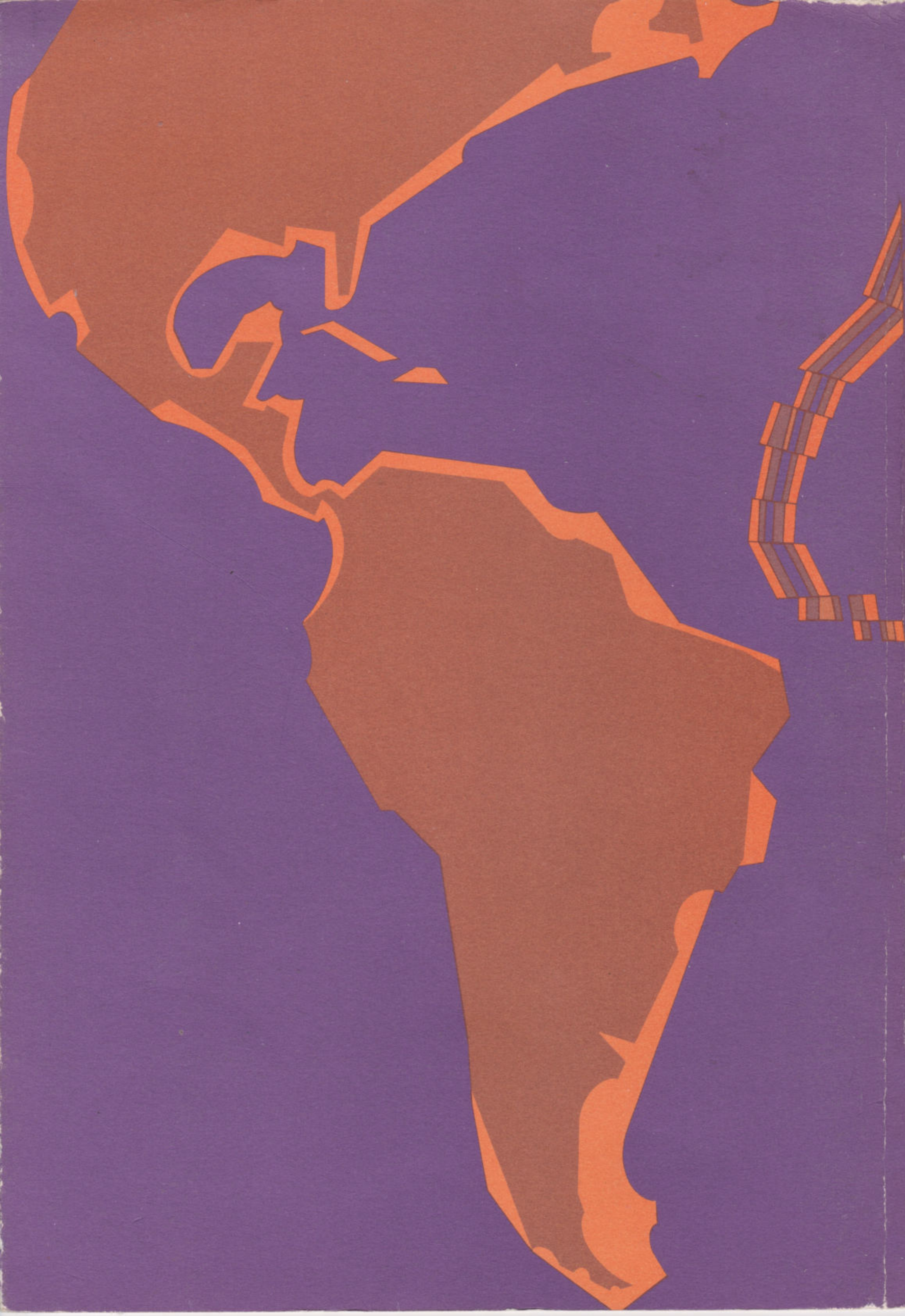
MRS. PATRICIA A. WILSON, Plate B, illustrations 1, 2, 3, 5, 6, 8 and 9; BRITISH MUSEUM, Fig. 32; BROOM'S BARN EXPERIMENTAL STATION, Suffolk, Fig. 6: HARPER AND ROW for Figs. 31 and 39 in A. N. Strahler, *The Earth Sciences*; INSTITUTE OF GEOLOGICAL SCIENCES for Plate B, illustrations 4 and 7; AEROFILMS for Fig. 23; MACMILLAN JOURNALS LTD. for Fig. 9 in *Nature*, Vol. 225, 17th Jan. 1970, and Fig. 35 in *Nature*, Vol. 225, Feb. 1970; THOMAS NELSON AND SONS for Figs. 2, 11 and 40 in A. Holmes, *Principles of Physical Geology*; PRENTICE-HALL INC. for Fig. 4 in Bloom, *Surface of the Earth*; JOHN WILEY AND SONS for Figs. 33A and B in Hill, *The Sea*, Vol. 3, and Figs. 32, 33 and 34 in Longwell, Flint and Sanders (eds.) *Physical Geology*.

UNIT 25

W. H. FREEMAN AND CO. for Figs. 7 and 15 in *Scientific American*, special issue, 'The Ocean', and Figs. 9, 11, SAQ 9 in *Scientific American*, Vol. 219, No. 6, Dec. 1968; HARPER AND ROW for Fig. 5 in A. N. Strahler, *The Earth Sciences*; MACMILLAN JOURNALS LTD. for Fig. 14 in *Nature*, Vol. 225, Jan. 1970; MERRILL PUBLISHING CO. for Fig. 3 in A. Miller, *Meteorology*; THOMAS NELSON AND SONS for Fig. 6 in A. Holmes, *Principles of Physical Geology*.

Notes

S.100—SCIENCE FOUNDATION COURSE UNITS



and plate tectonics